A new era in the quest for Dark Matter

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15/6/2021, Quantum Universe Colloquium

GRAPPA

GRavitation AstroParticle Physics Amsterdam

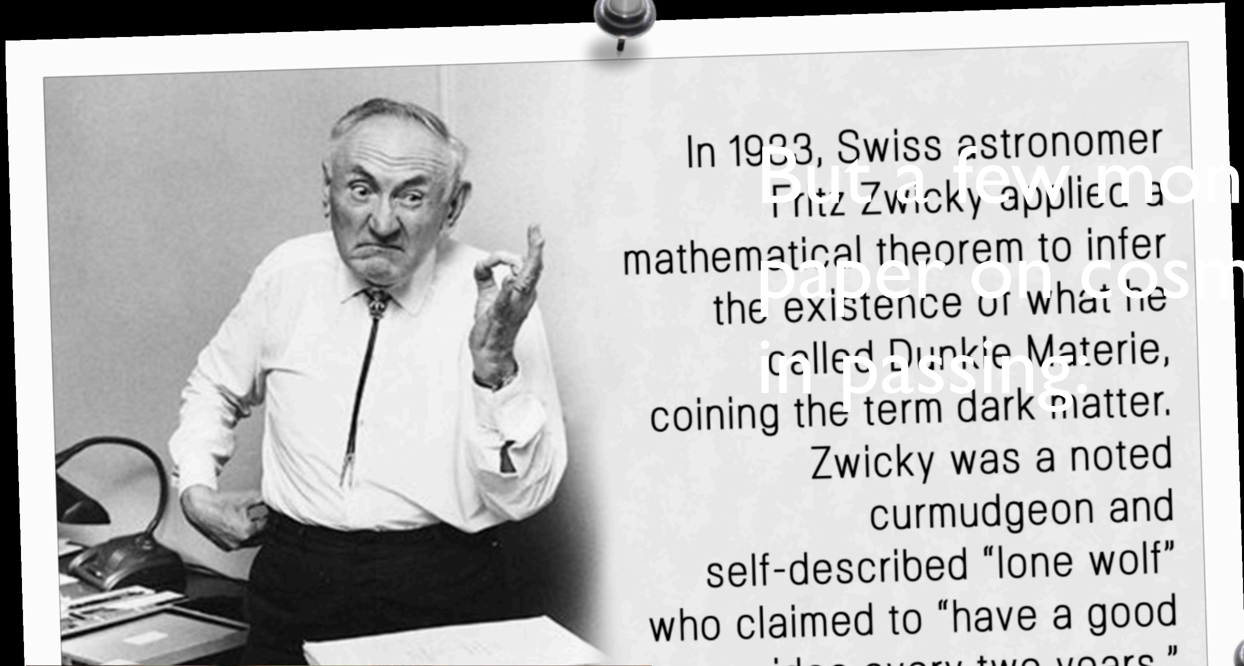
Plan of the talk:

Preamble: the dark universe *narrative*

Part I: DM - what have we learnt?

Part II: A new era in the quest for DM

Dark matter: a problem with a long history..

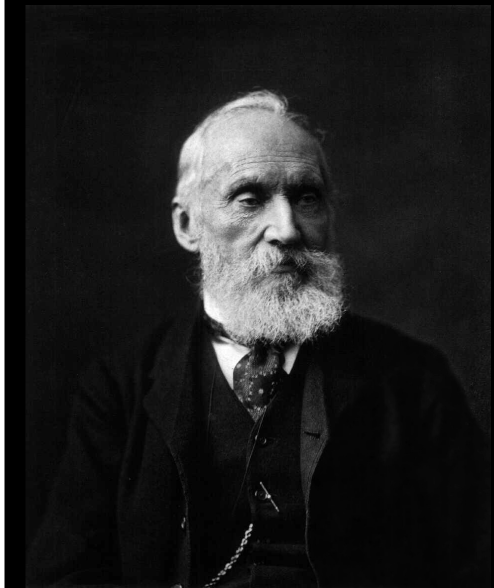


But a few months earlier, in a paper on cosmic rays, he wrote in passing:

The ratio a/b is equal at the very least to a hundred. It is therefore impossible that the cosmic rays, if photons, come from luminous matter. Now according to the present estimates the average density of dark matter in our galaxy (ρ_g) and throughout the rest of the universe (ρ_u) are in the ratio

$$\rho_g/\rho_u > 100{,}000. \quad (8)$$

Dark matter: a problem with a long history..



Lord Kelvin (1904)

"Many of our stars, perhaps a great majority of them, may be dark bodies."

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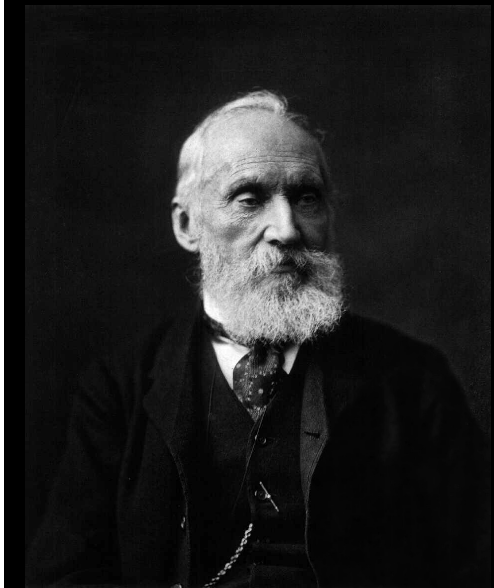

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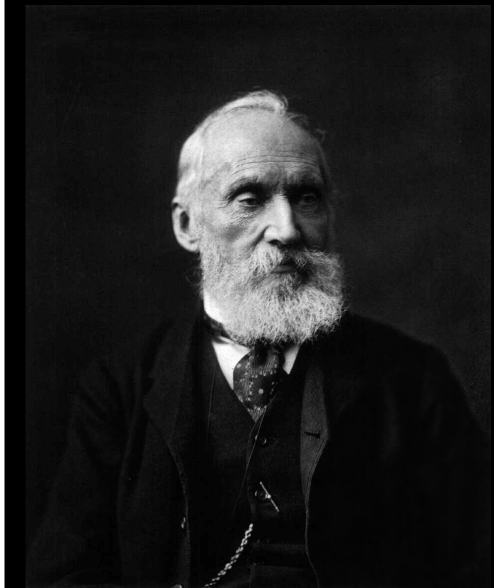

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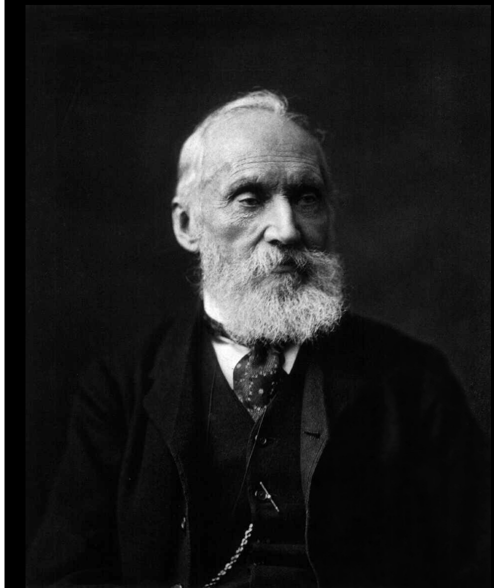

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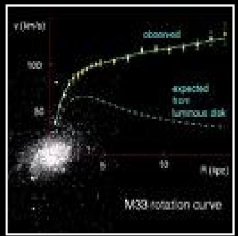
Fritz Zwicky (1933)

"If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter"

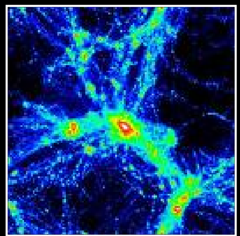
"A history of Dark Matter" GB & Hooper - RMP *1605.04909*
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

What is the Universe made of?

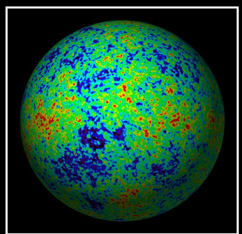
OBSERVATIONS



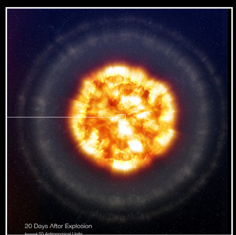
- Rotation Curves



- Clusters of galaxies

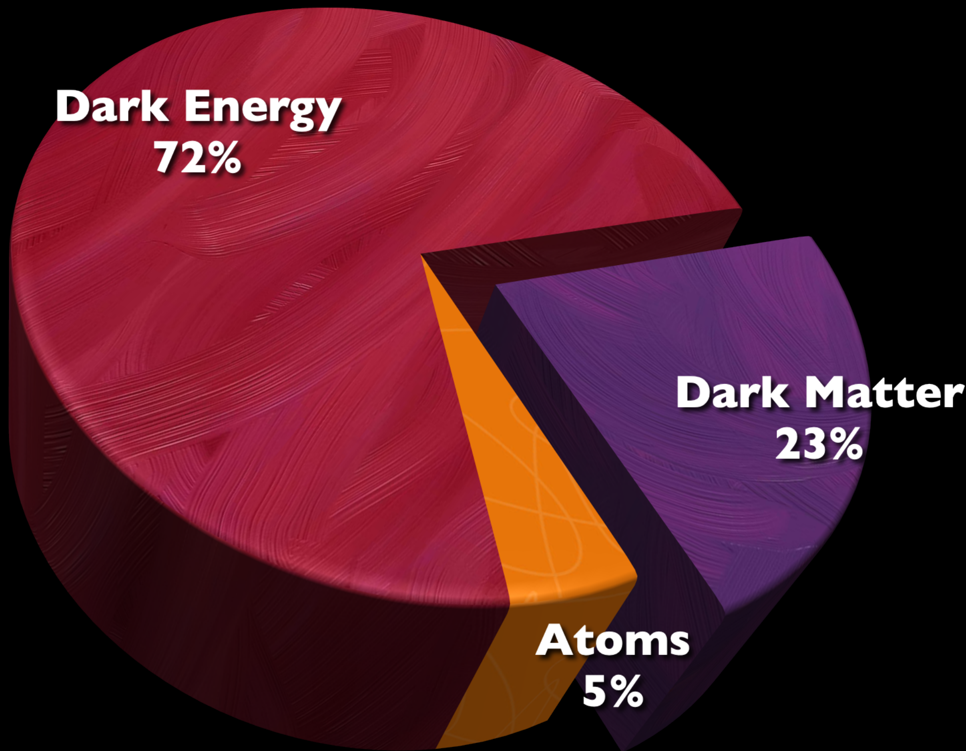


- CMB



- Type Ia Supernovae

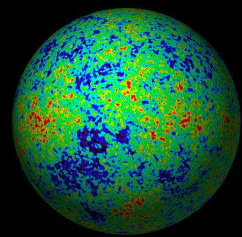
...

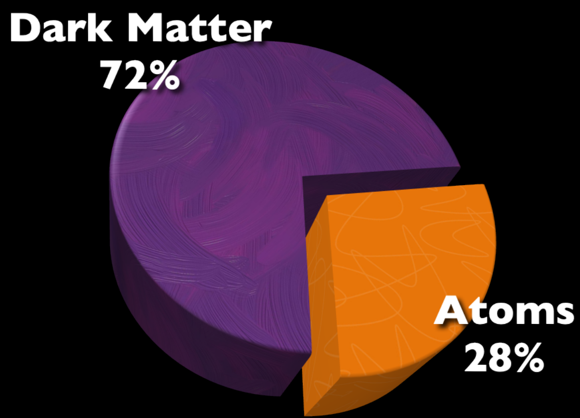


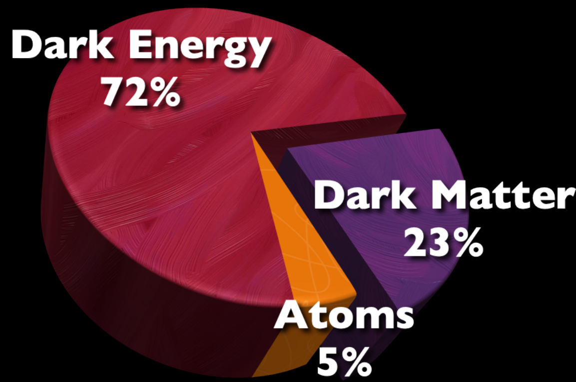
[statement valid *now*, and on *very large scales*]

What is the Universe made of?

Posti & Helmi, A&A 621,A56 (2019)

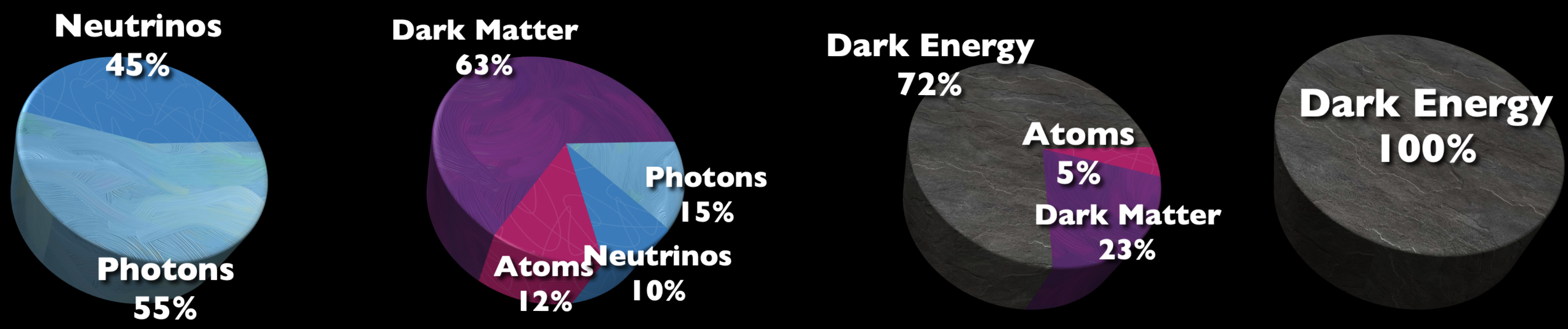




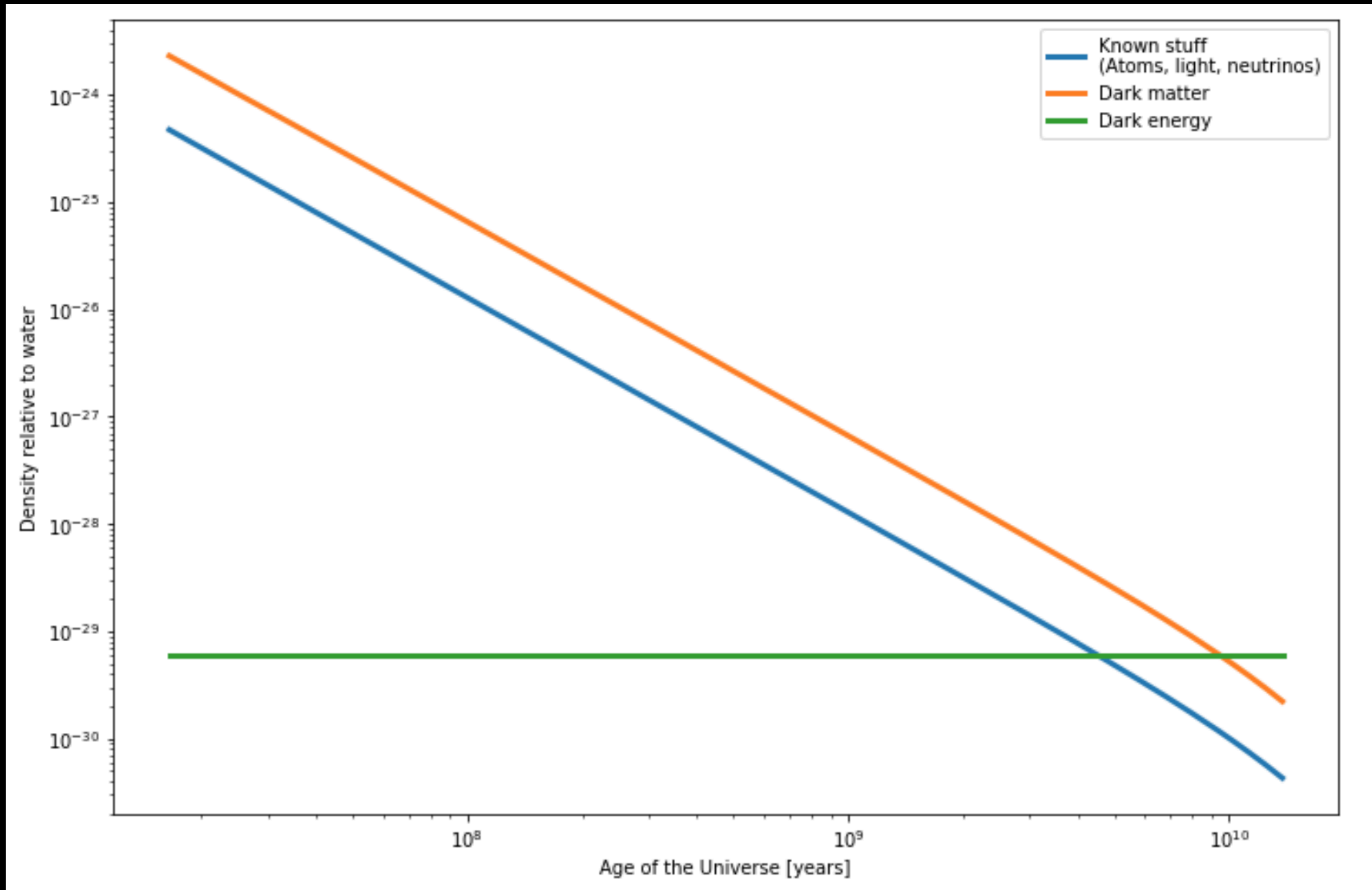


What was the Universe made of?

At BBN | At recombination | Today | …eventually



Evolution of matter/energy density



Created with #astropy https://astropy.org, astropy.cosmology package https://docs.astropy.org/en/stable/cosmology/

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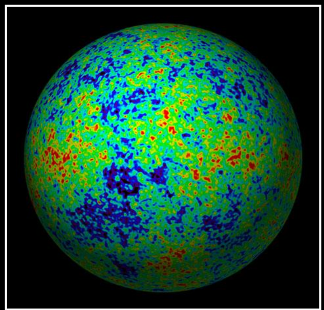
Simulating the Universe

http://www.illustris-project.org/media/

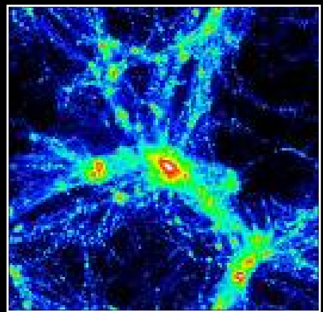
What do we know?

In order to be considered a viable DM candidate,
a new particle has to satisfy a number of conditions:

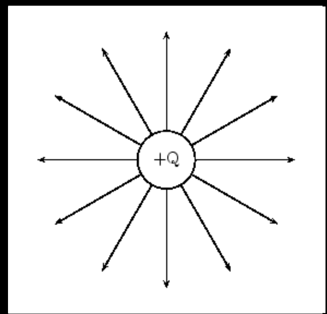
1) Abundance ok?



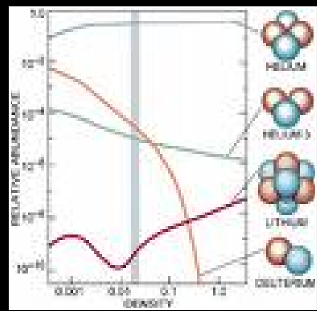
2) Cold?



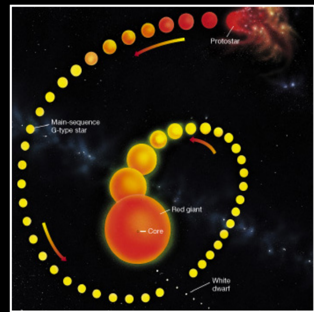
3) Neutral?



4) BBN ok?



5) Stars OK?



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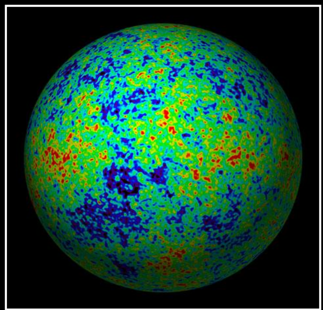

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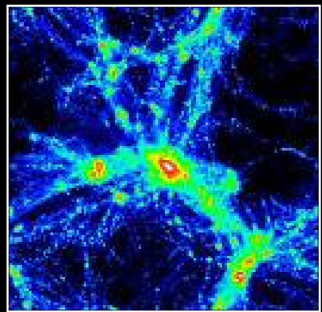

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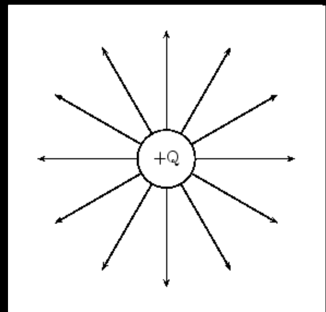

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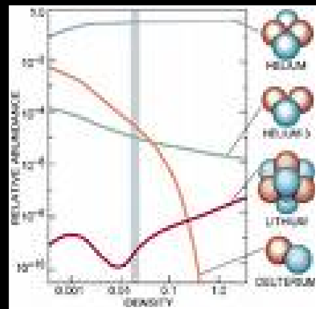

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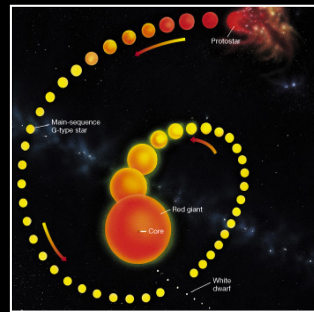
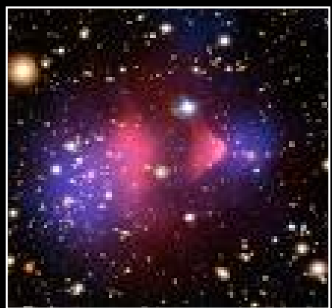
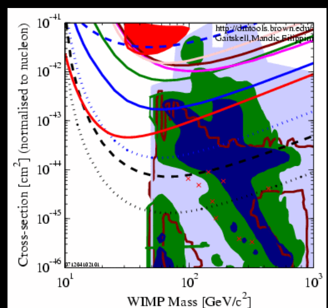


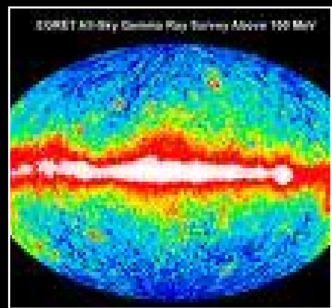
6) Collisionless?



7) Couplings OK?



8) γ-rays OK?

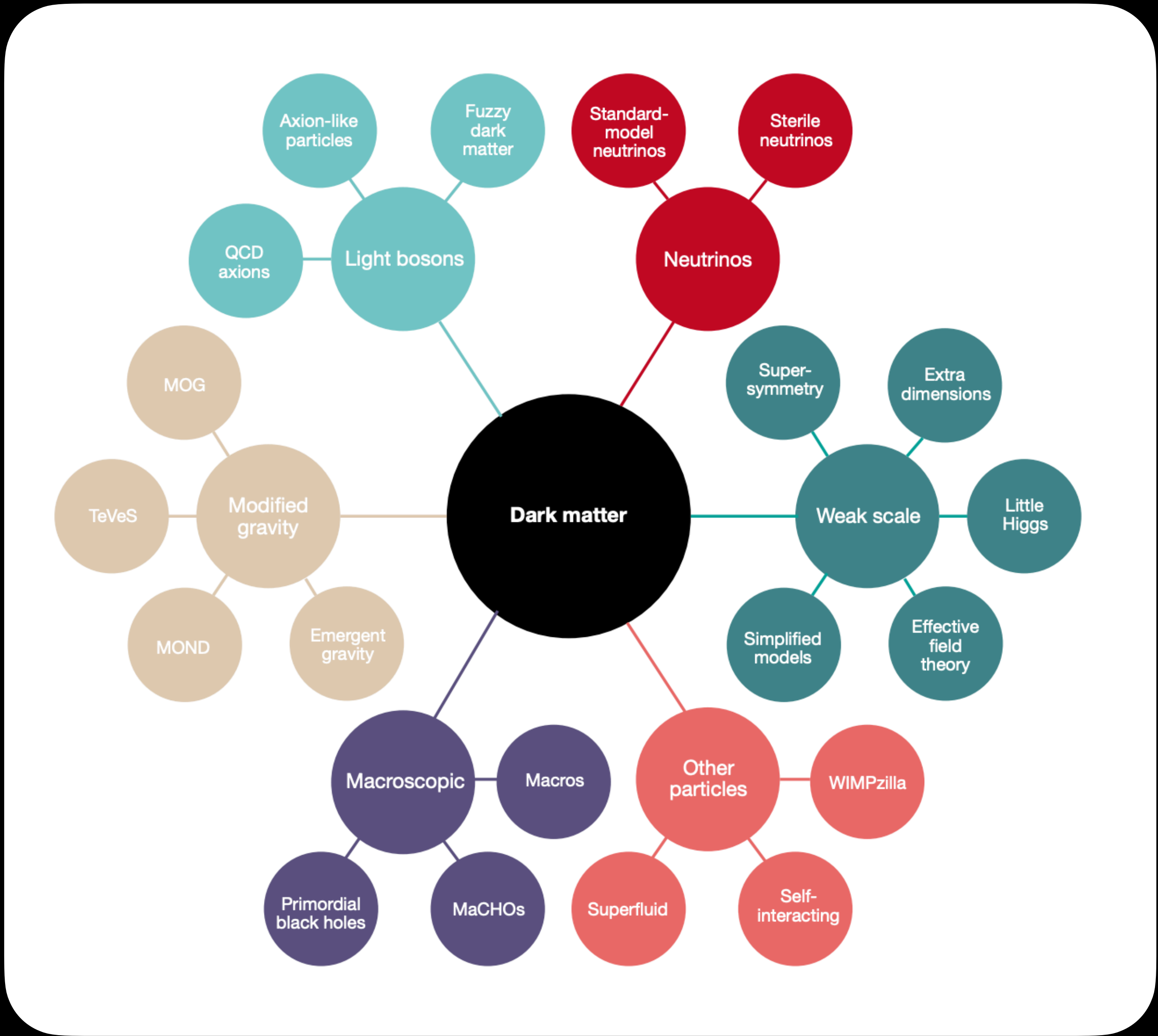


9) Astro bounds?

10) Can probe it?

Taoso, Bertone, Masiero 0711.4996

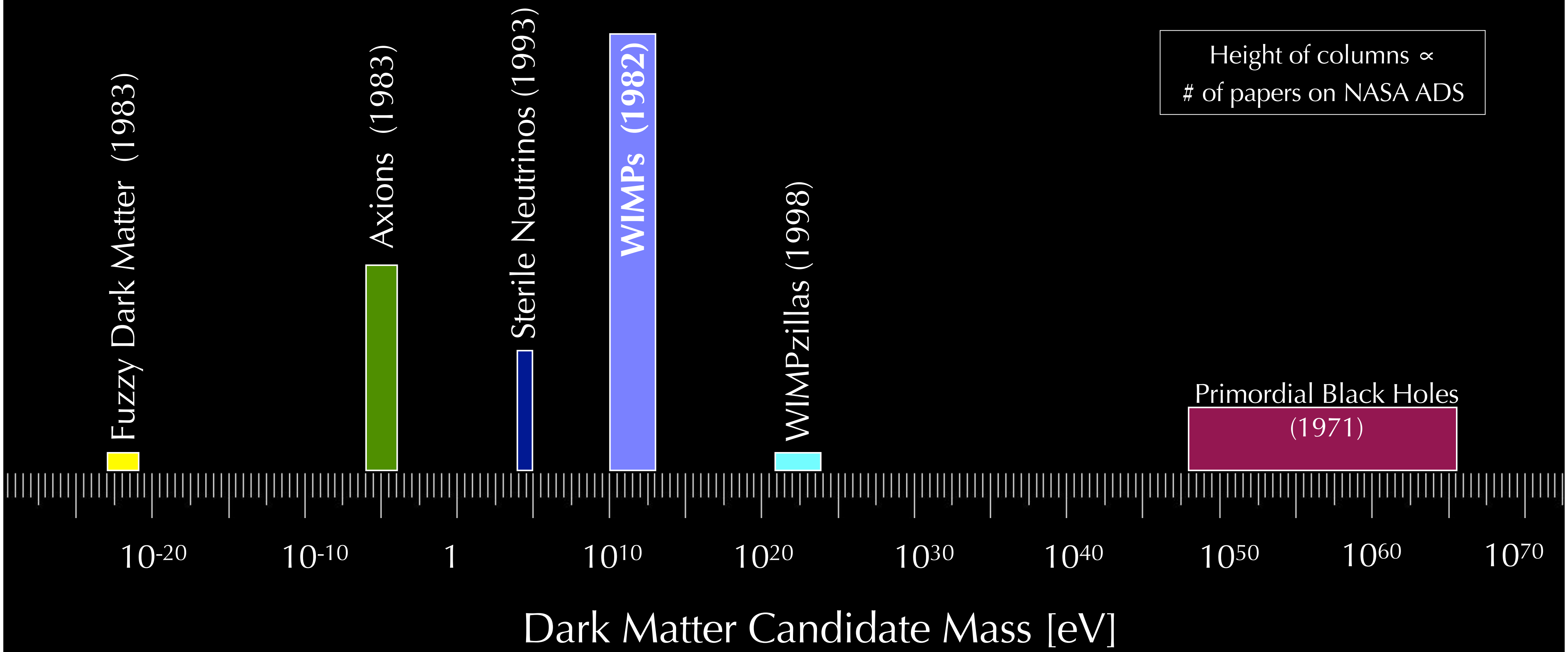
Candidates



GB, Tait, *Nature (2018)1810.01668*

Candidates

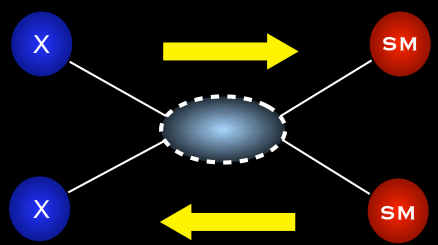
- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



WIMPs

By far the most studied class of dark matter candidates.

The WIMP paradigm is based on a simple yet powerful idea:



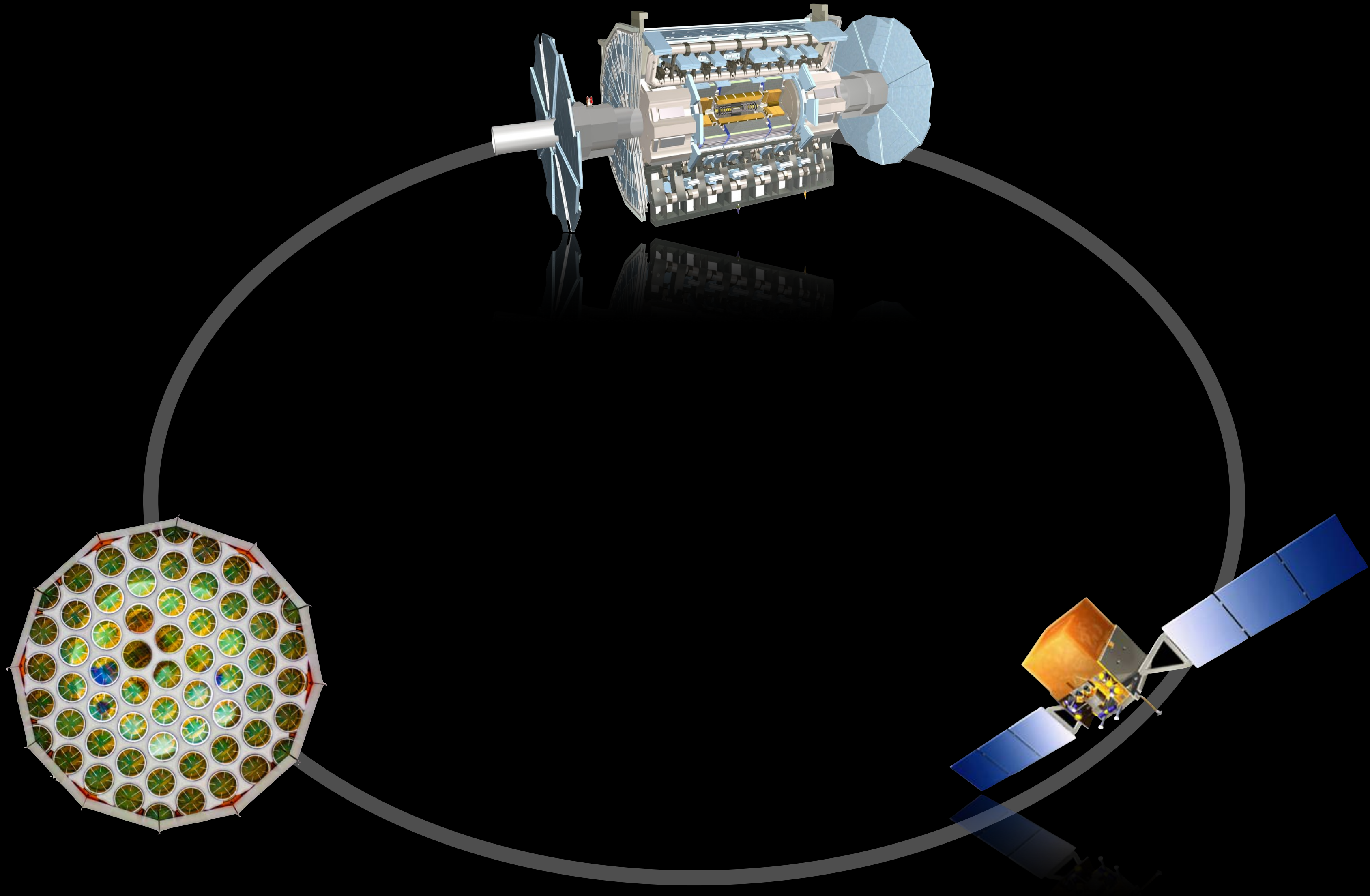
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Weak-scale cross sections can reproduce observed relic density

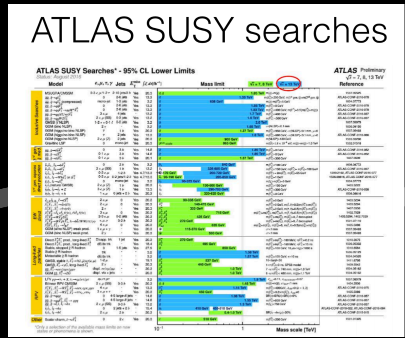
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

‘WIMP miracle’: new physics at ~1TeV solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM

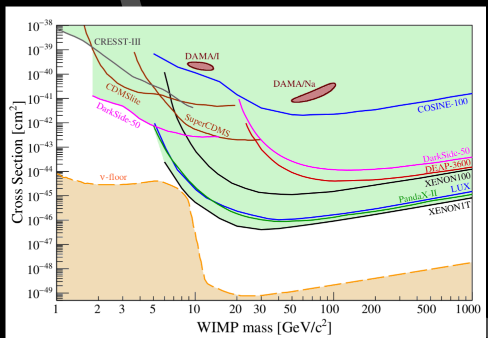
WIMPs searches

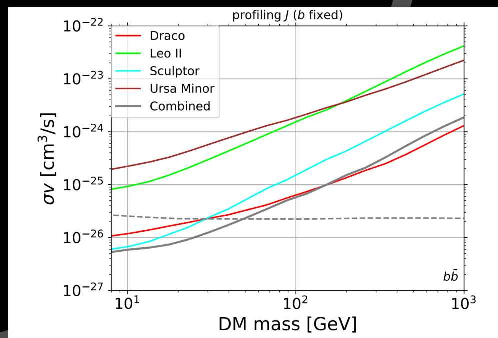


WIMPs searches



No WIMPs
found yet, despite many efforts!





Are WIMPs ruled out?

NO

absence of evidence $\neq$ evidence of absence

Are WIMPs ruled out?

Absence of evidence has dampened the enthusiasm for WIMPs, but:

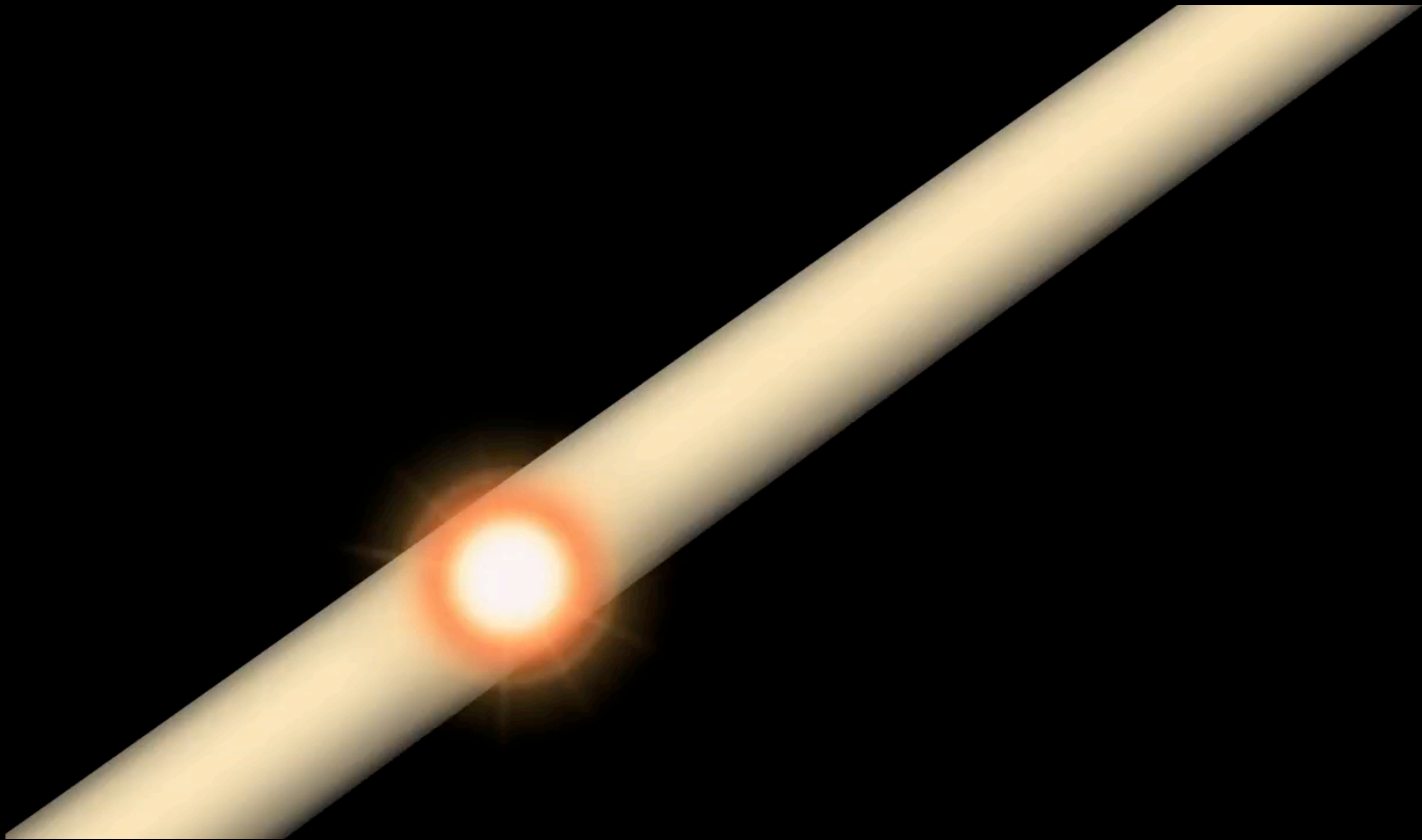
- Large portions of the parameter space of specific WIMP candidates remain viable *[Leane+ 1805.10305, Beekveld+ 1906.10706, Blanco+ 1907.05893,…]*
- WIMP paradigm ≠ WIMP miracle *[Arakawa and Tait 2101.11031,…]*
- Clear way forward:
  - 15 years of LHC & HL-LHC data
  - Direct detection experiments all the way to "neutrino floor"
  - Non-dedicated Indirect Detection experiments

A new era in the search for DM

GB, Tait, *Nature (2018)1810.01668*

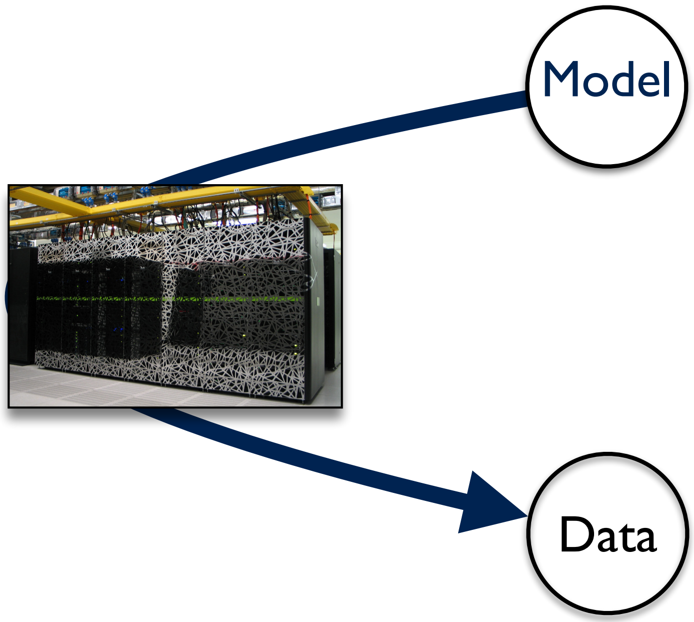
I. Broaden/improve/diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

Dark matter searches at the LHC



Improving existing strategies

Speeding up statistical inference with Machine Learning tools



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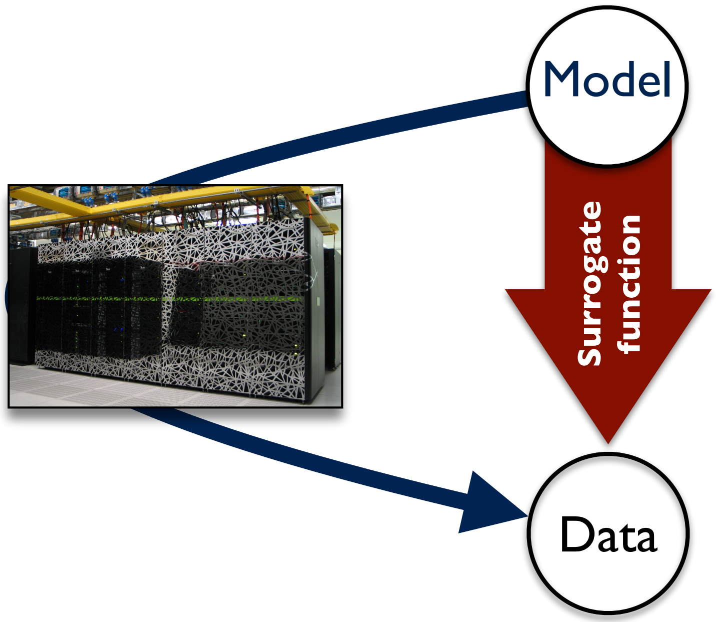
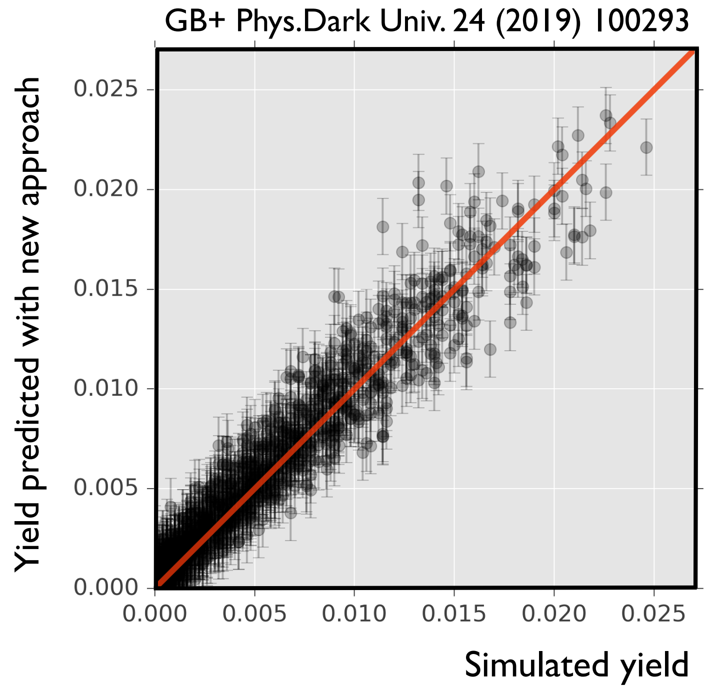




- Exploring parameter spaces of theoretical models computationally expensive
- Machine learning methods (*distributed gaussian processes*, *deep neural networks*) bring computation time from ~CPU *centuries* to ~CPU *weeks*!
- Can be run by a PhD student in 1 day on a desktop computer!

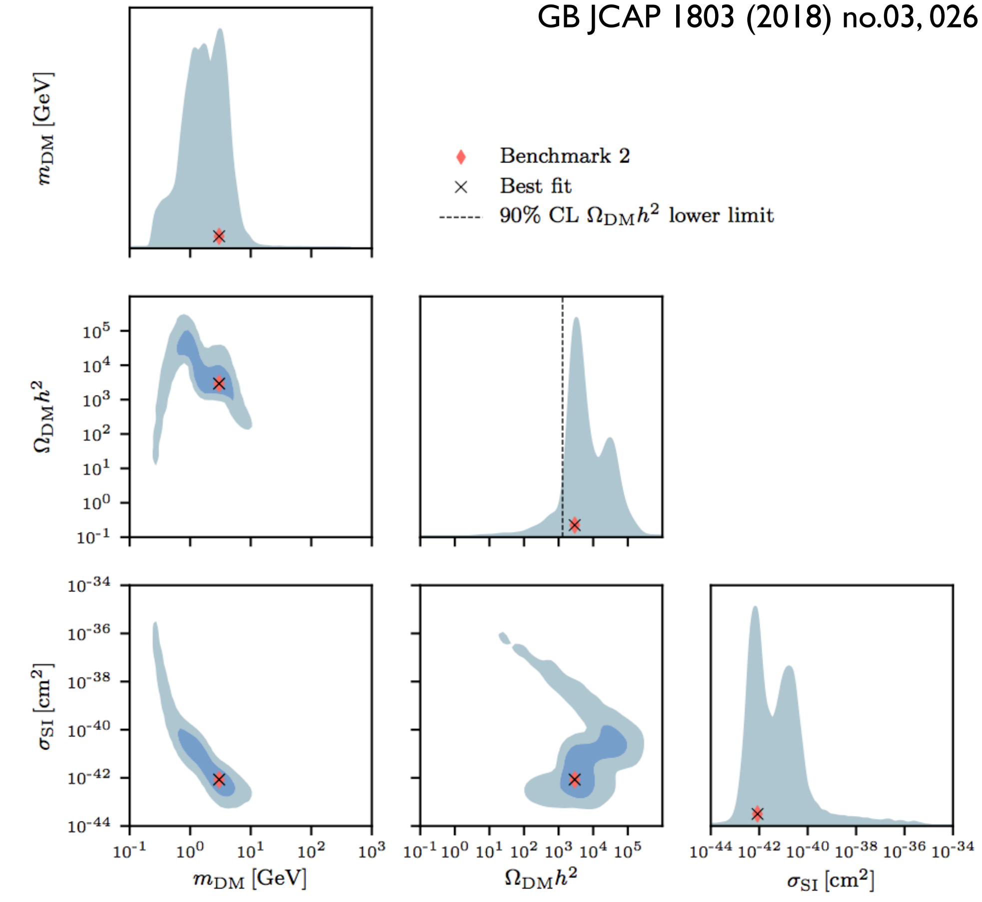
Improving existing strategies

E.g. New Machine Learning tools applied to LHC searches:

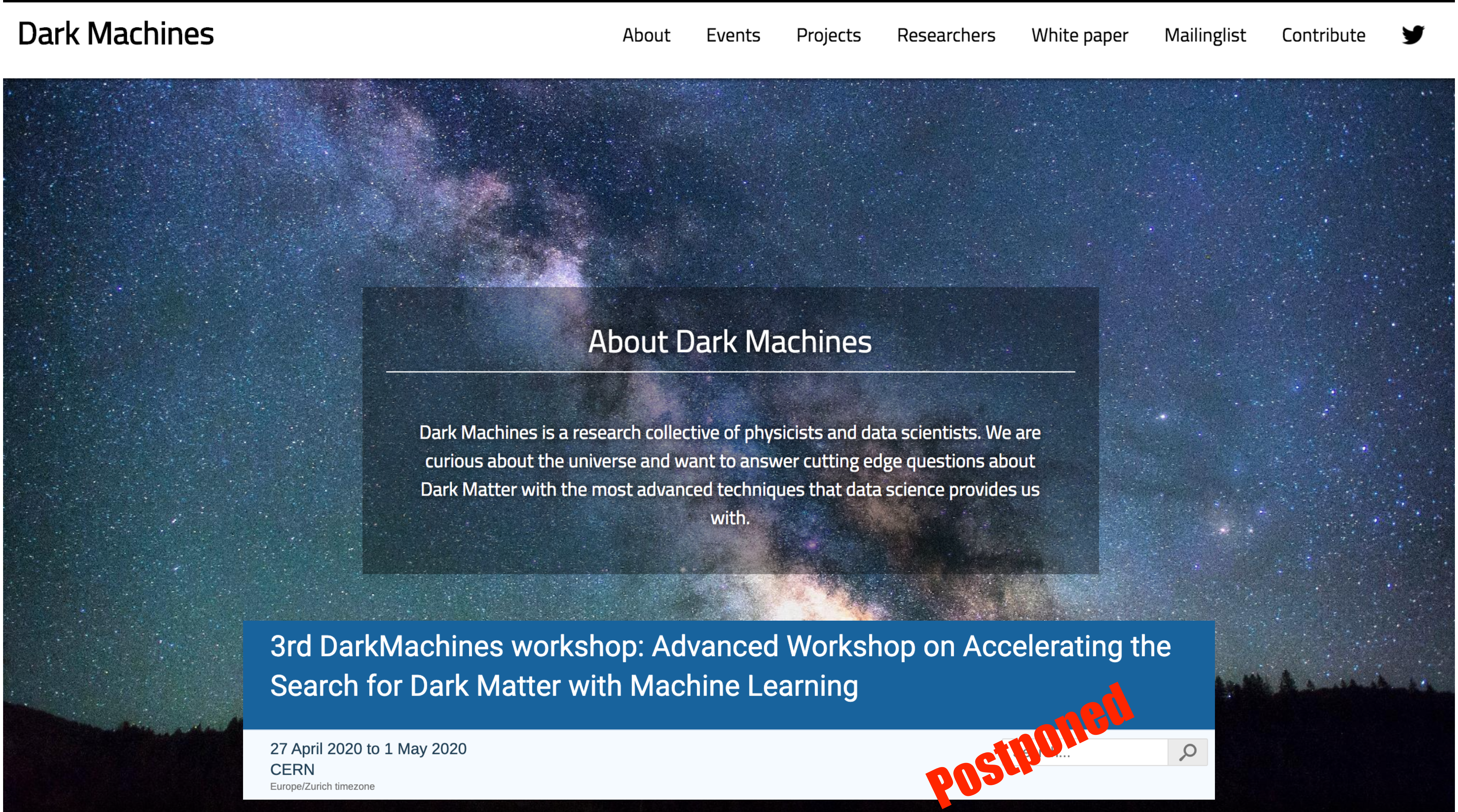
i) Fast exploration of phenomenology in high-dimensional parameter spaces

ii) Perform fast inference if new particles discovered, that allows us to recover theory parameters compatible with data

GB JCAP 1803 (2018) no.03, 026



The *Dark Machines* initiative



Website: darkmachines.org ; Twitter: dark_machines

A new era in the search for DM

GB, Tait, *Nature (2018)1810.01668*

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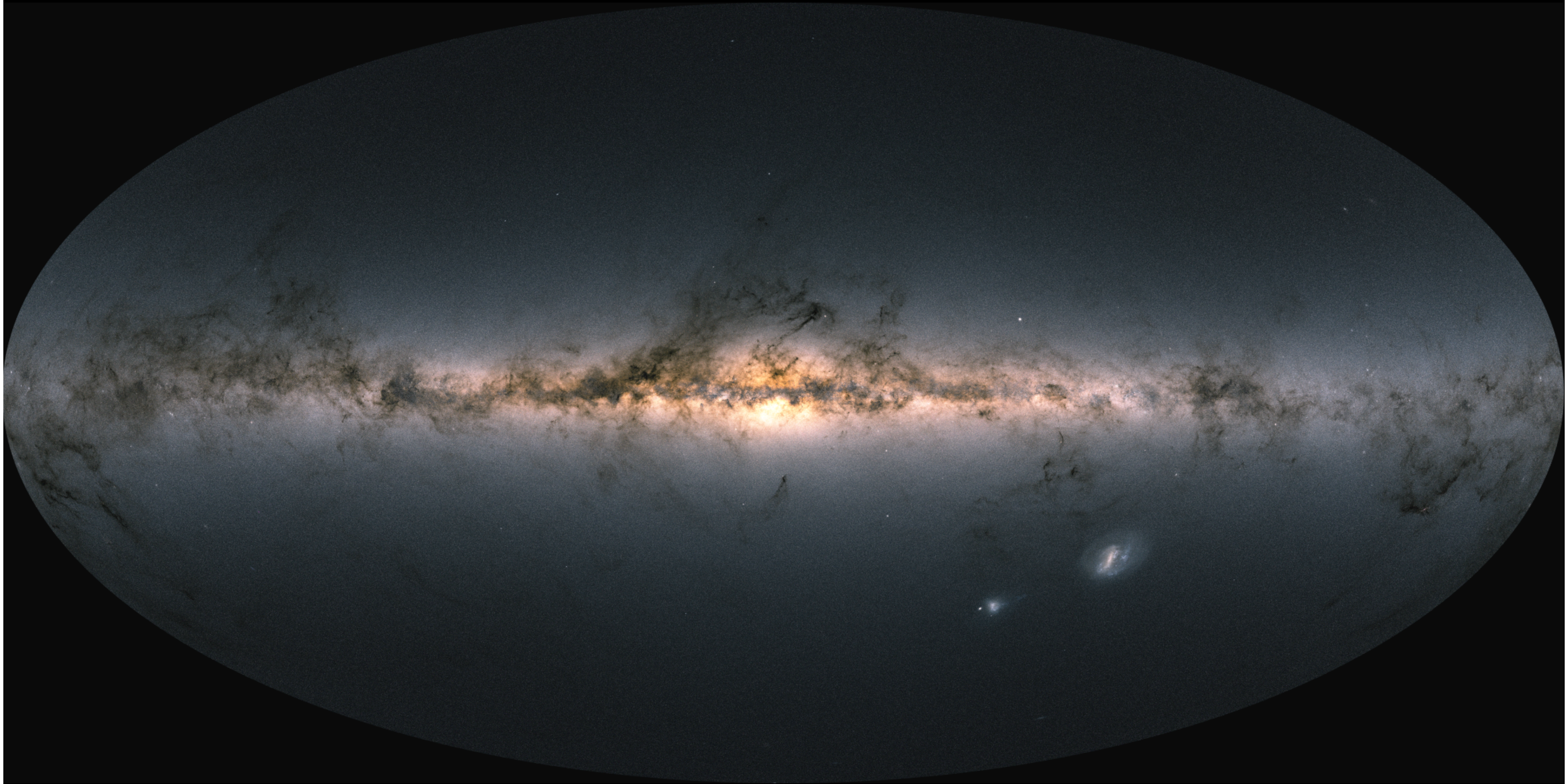
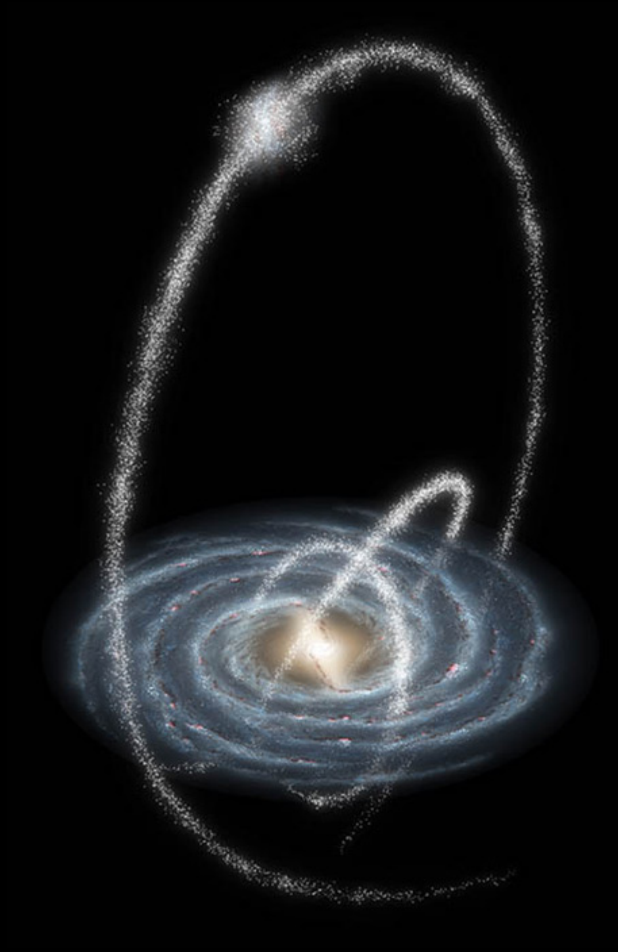
GAIA'S SKY

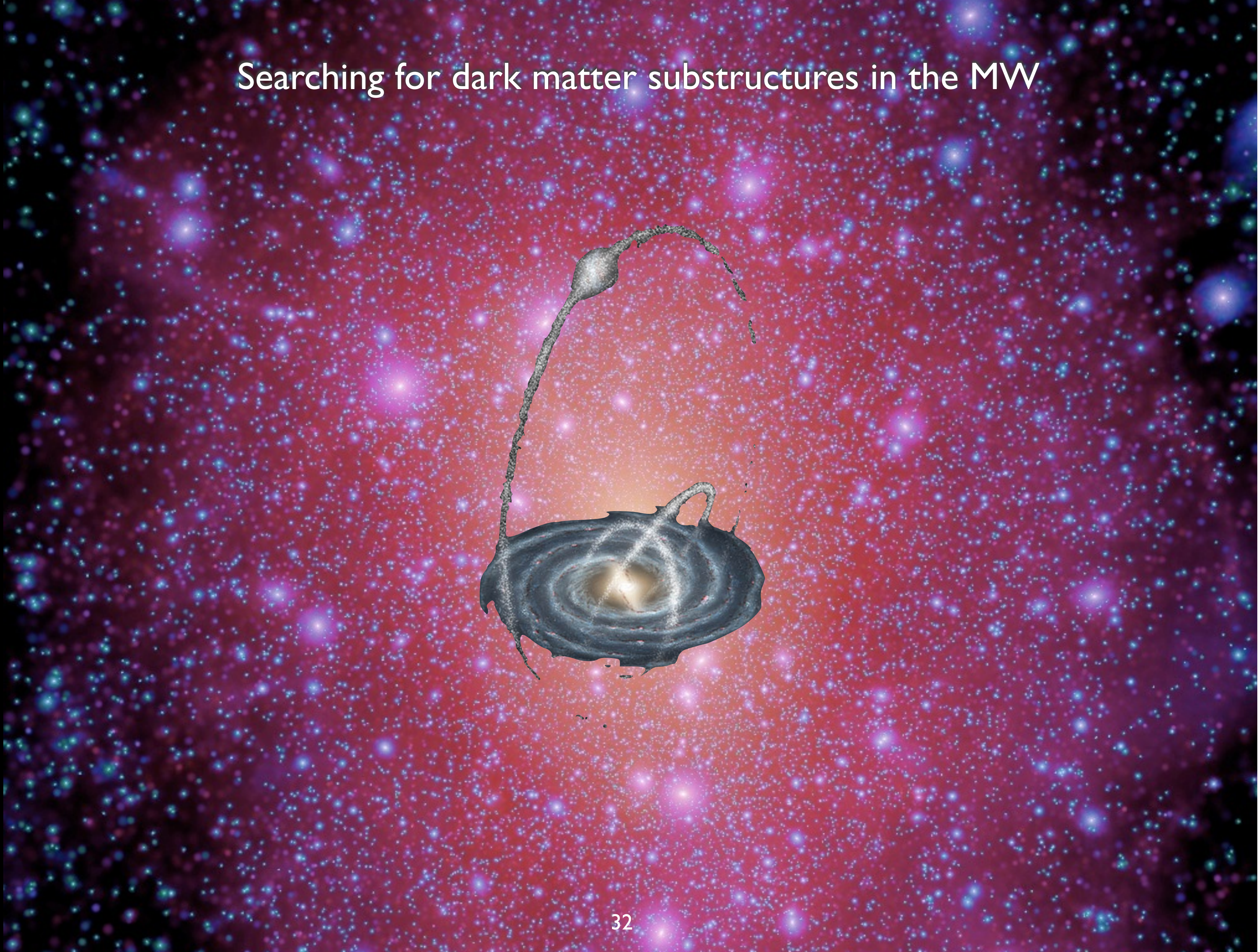


Total brightness and colour of stars observed by ESA's Gaia satellite and released as part of Gaia's Early Data Release 3

Stellar streams



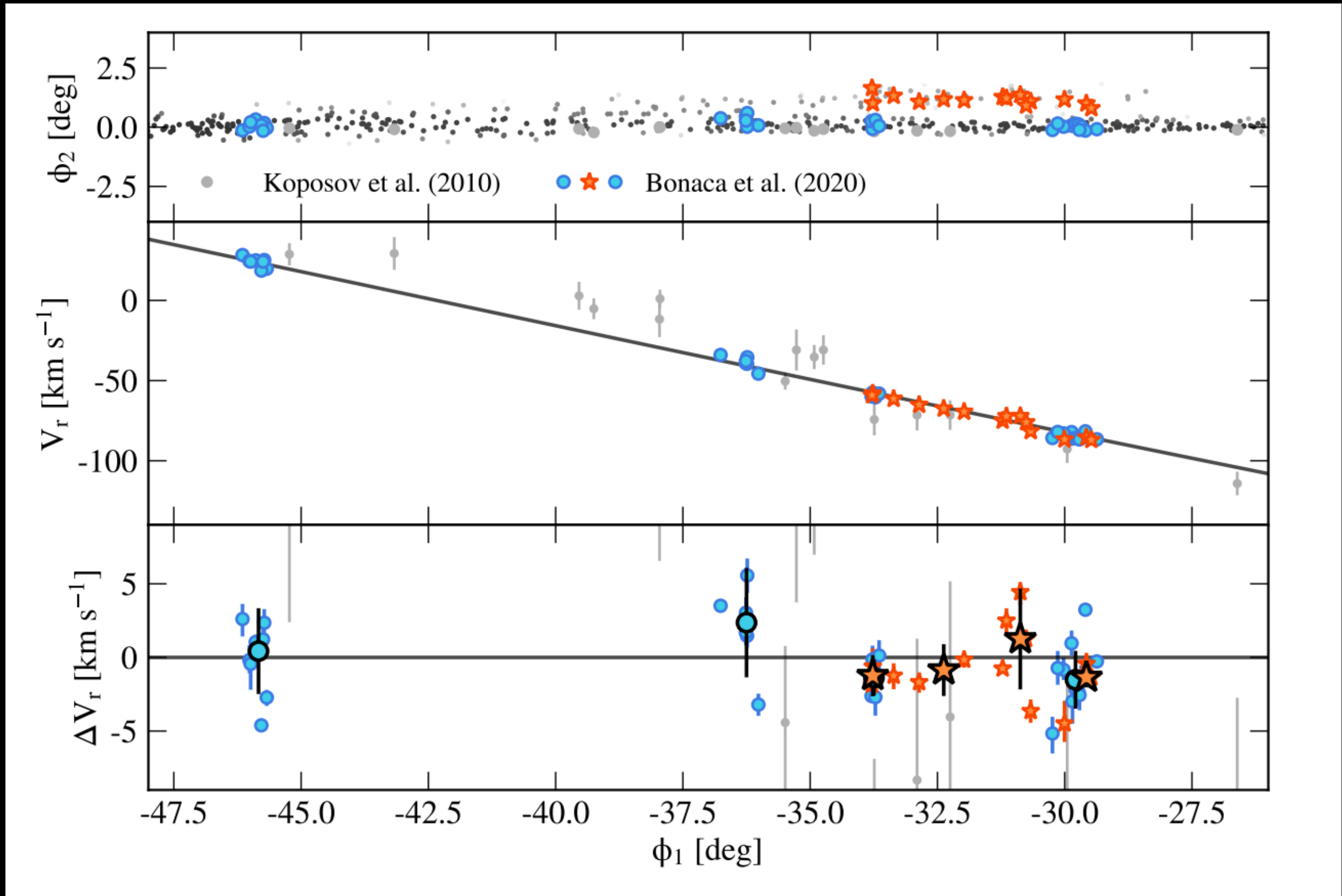
Searching for dark matter substructures in the MW



Gaia GD1 stream data!

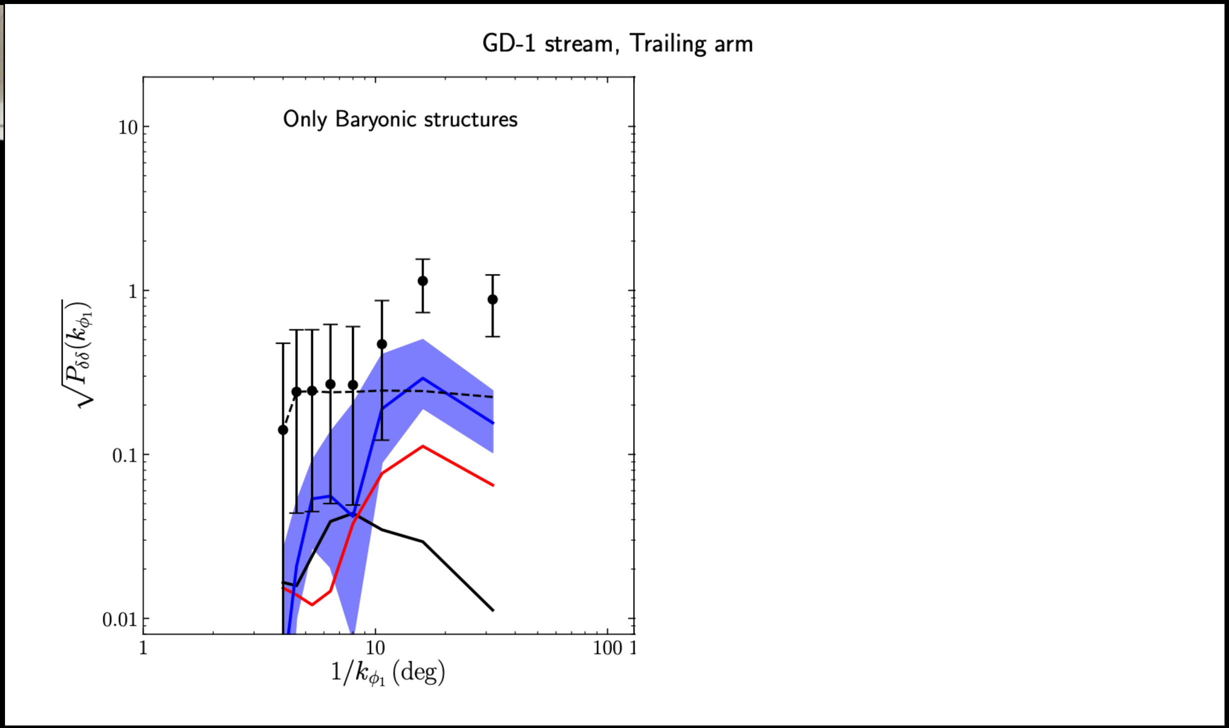
New map of stars in GD1 stream (longest cold stream in the MW) with *Gaia* second data release combined with *Pan-STARRS*.

Stream appears to be perturbed, with several 'gaps' and a 'spur'



Bonaca et al. 2001.07215

Statistical analysis of perturbations: Strong hints of dark substructures!

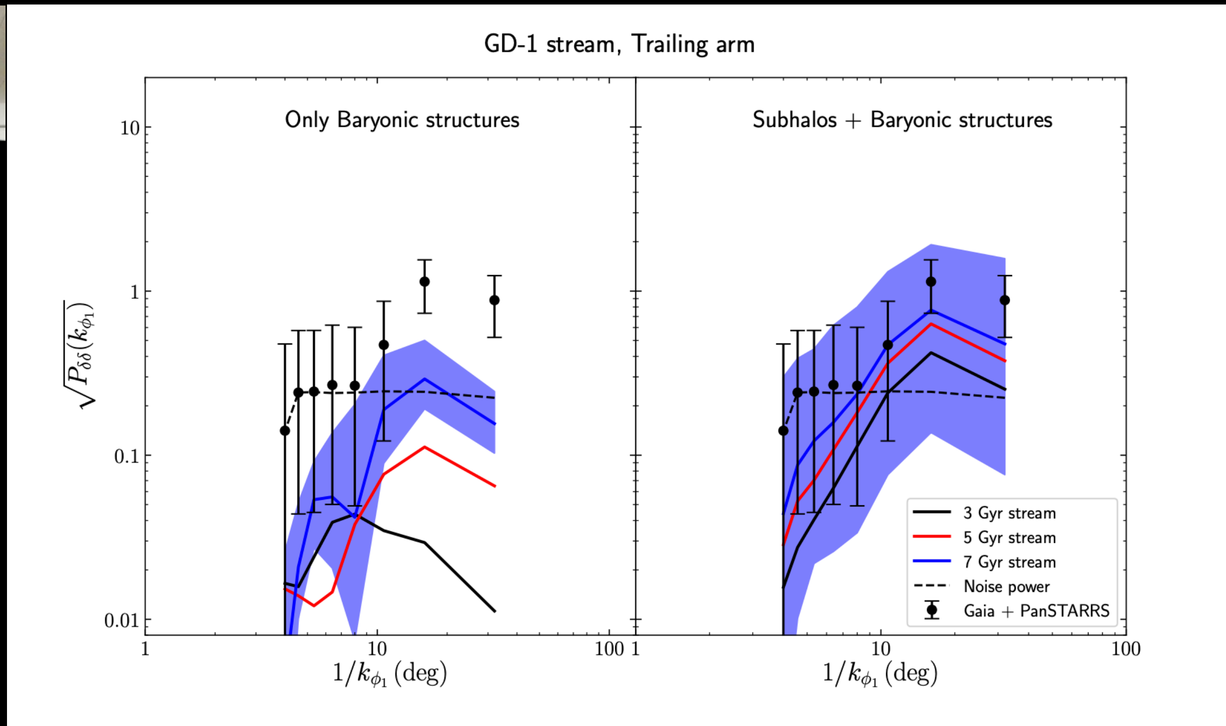


Banik, Bovy, GB, Erkal, de Boer, MNRAS 502, 2364 (2021)

- Gaia GD1 stream data exhibit substantial 'structure'

- Density fluctuations cannot be explained by "baryonic" structures (GC, GMC, spiral arms etc)

Statistical analysis of perturbations: Strong hints of dark substructures!

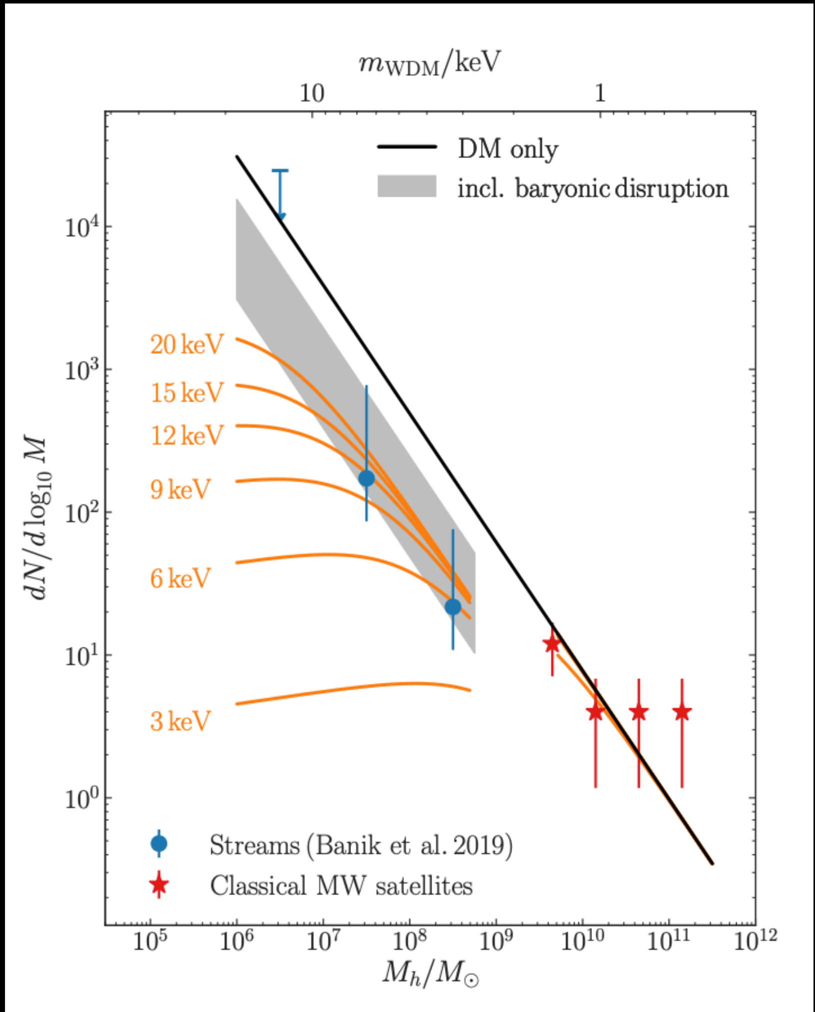


Banik, Bovy, GB, Erkal, de Boer, MNRAS 502, 2364 (2021)

-Density fluctuations are consistent with CDM predictions (not a fit!)

-Likelihood-free method based on approximate likelihood ratios -> more stringent bounds (Hermans et al. 2019)

Statistical analysis of perturbations: Stringent constraints on the nature of DM

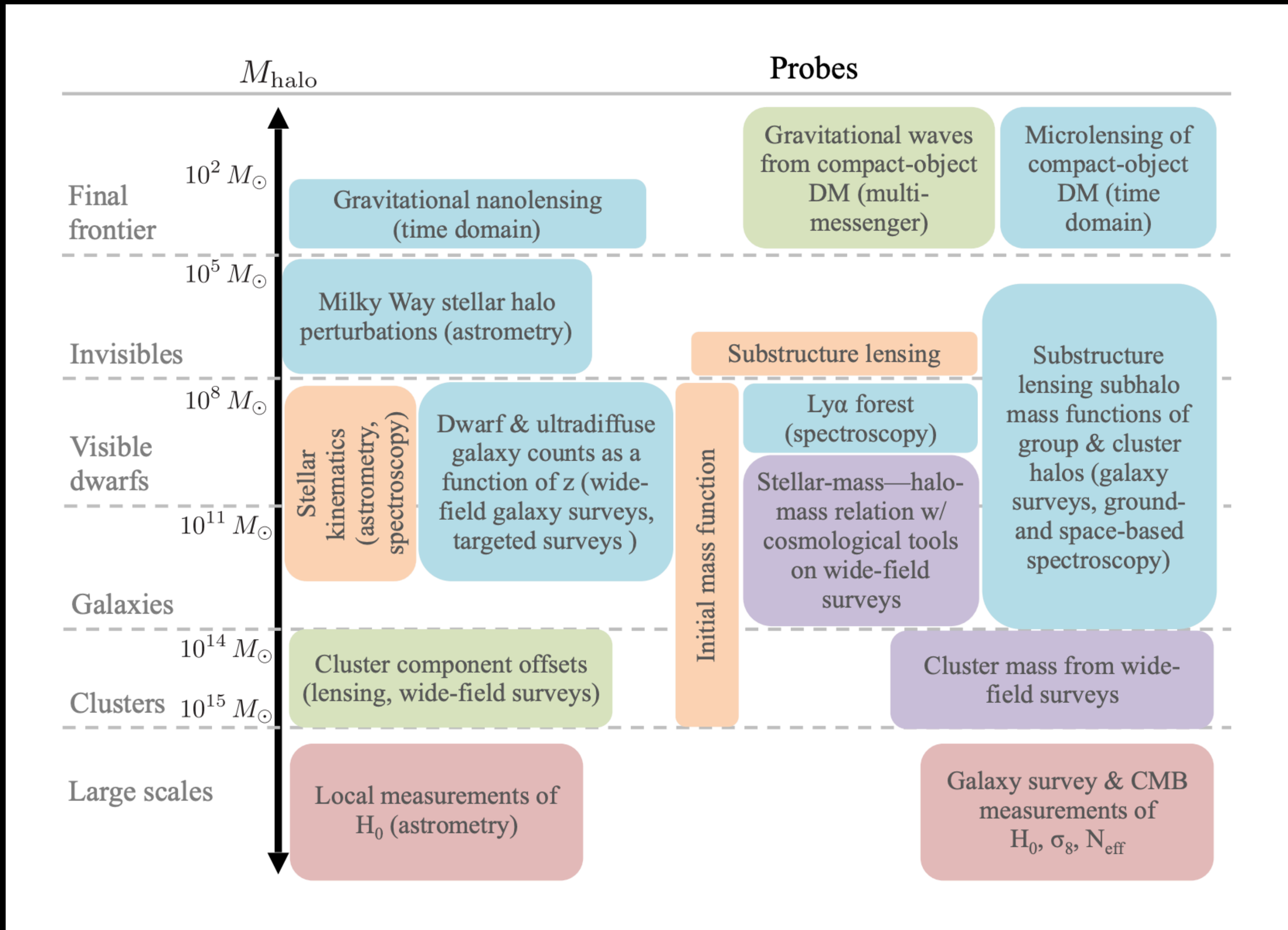


1911.02663

Constraints on the particle mass of dark matter candidates such as warm, fuzzy, and self-interacting dark matter

See also 2001.11013, 2001.05503.

Gravitational probes of dark matter physics



M. Buckley and A. Peter, Physics Reports, 761, 1-60 (2018)

The future of dark matter searches

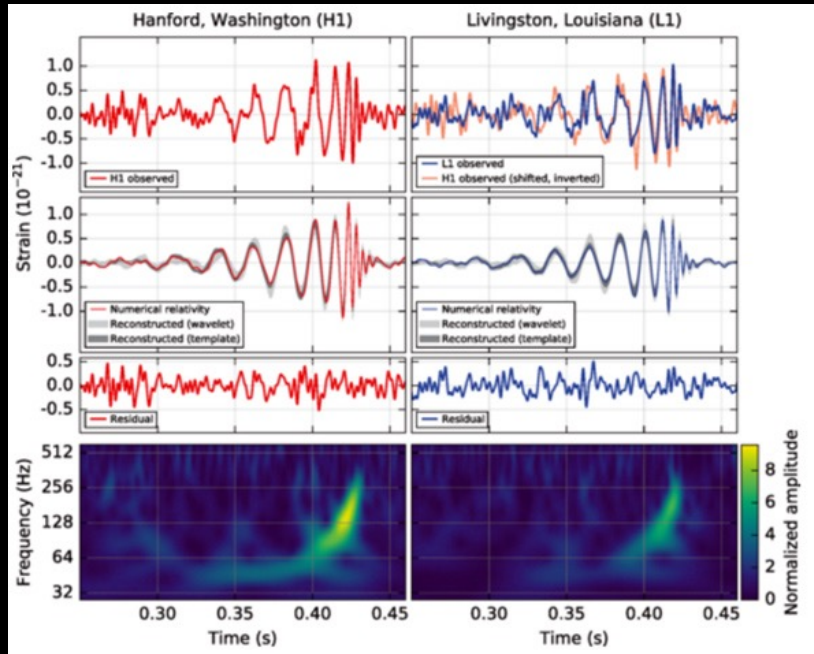
I. Broaden/improve/diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

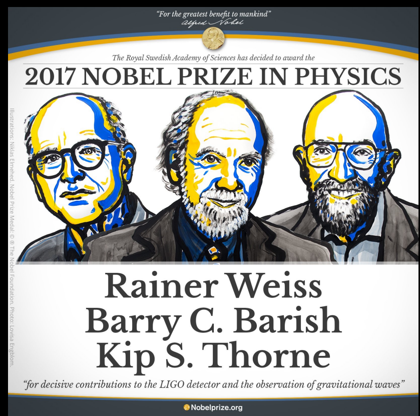
Gravitational Waves

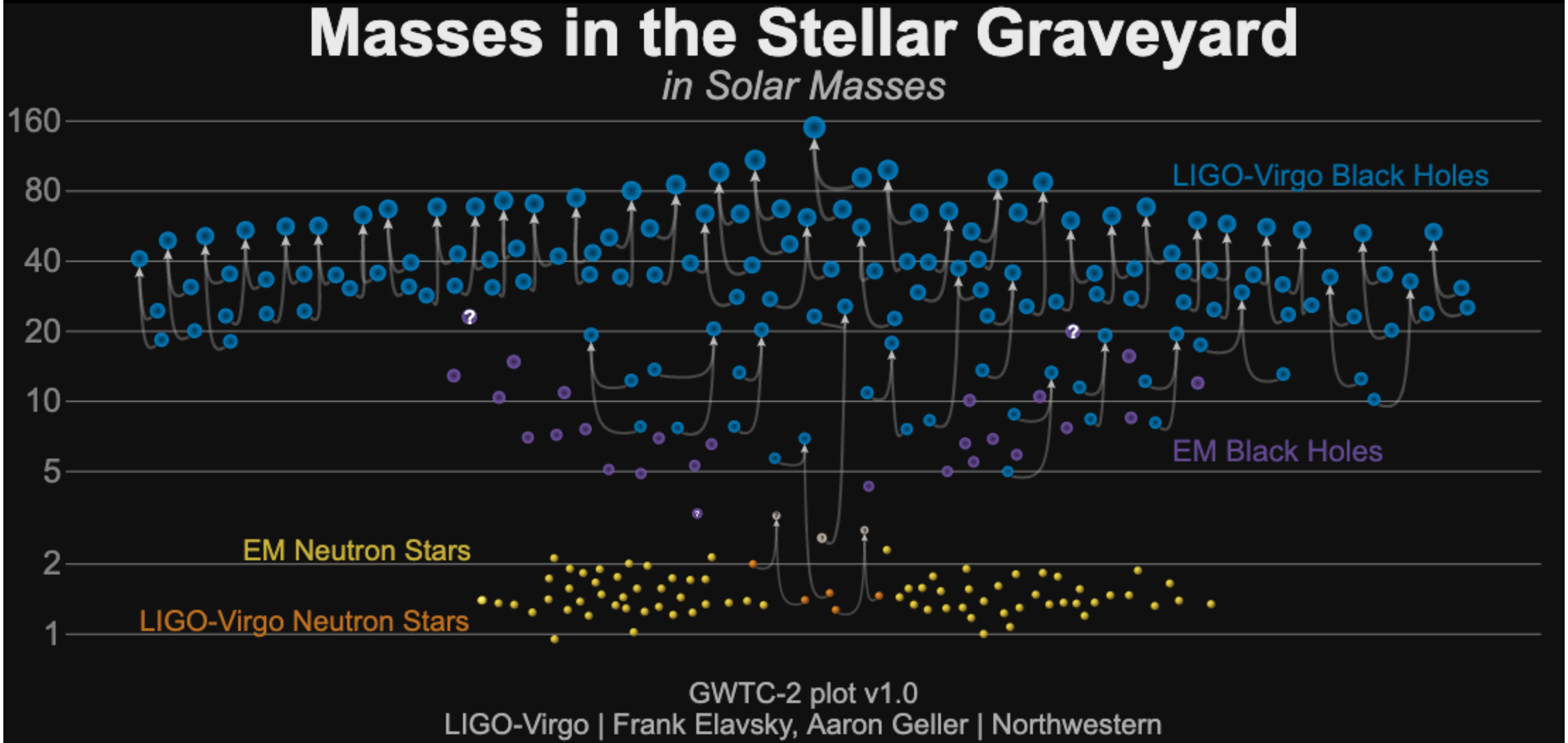
"The discovery that shook the world"

LIGO & Virgo coll, PRL 116, 061102

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$

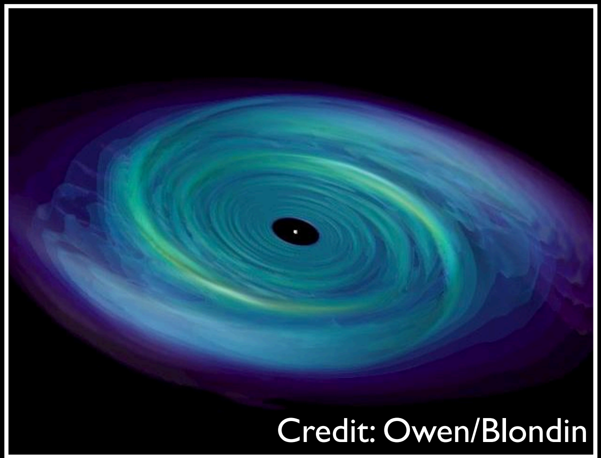




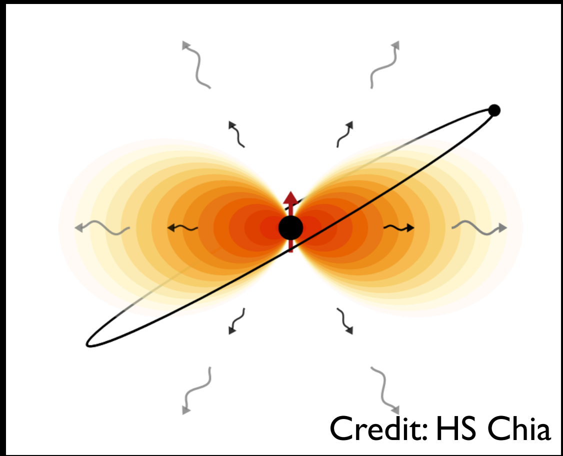


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

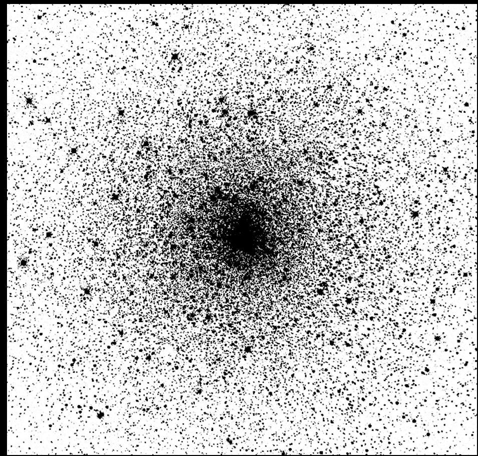
Black Hole environments



Accretion discs
(e.g. 1810.03623 and refs therein)

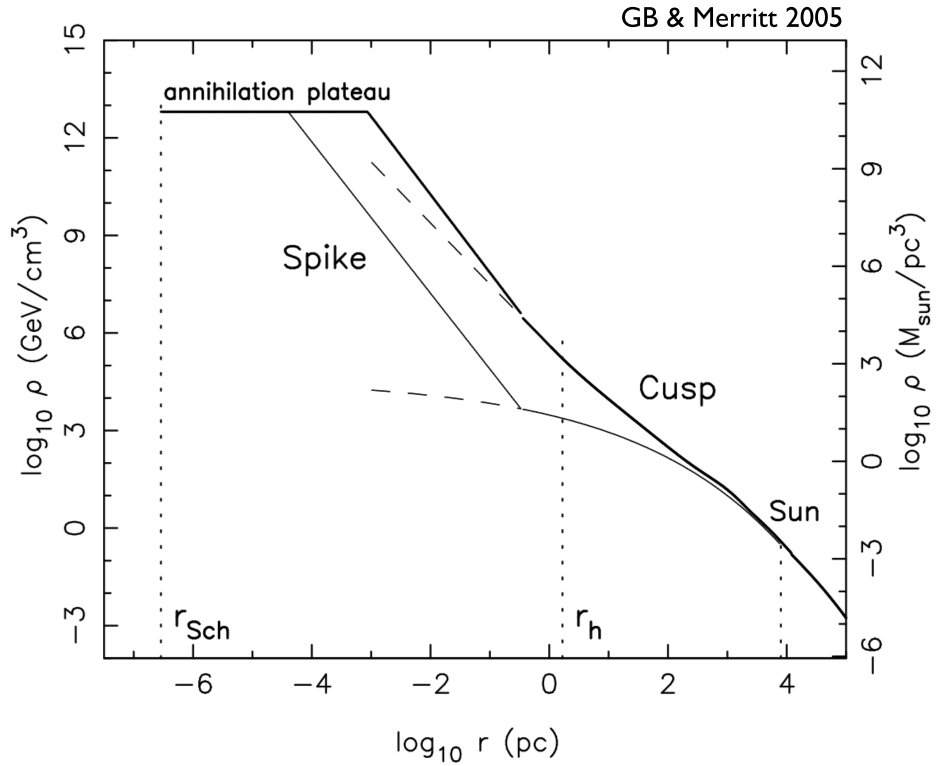


Gravitational “atoms”
(e.g. 1912.04932 and refs therein)



Dark Matter “spikes”
(e.g. 2002.12811 and refs therein)

Dark Matter ‘dress’ around BHs



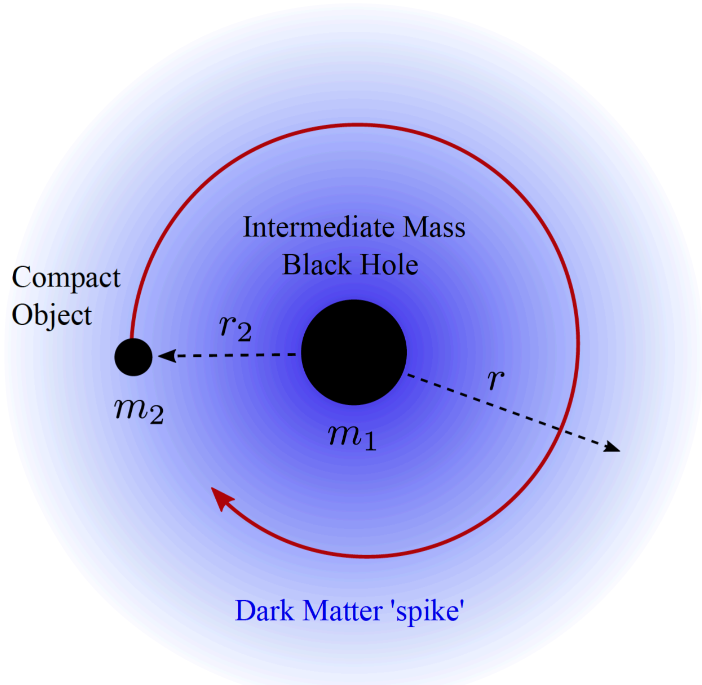
- **Adiabatic ‘spikes’ around SMBHs**
  (Gondolo & Silk 2000; …)
- **‘Mini-spikes’ around IMBHs**
  (GB, Zentner, Silk 2005; …)
- **Overdensities around primordial BHs**
  (e.g. Boudaud+ 2106.07480)

Open questions: astrophysical uncertainties, dependence on DM properties (self-interactions, annihilations)

Dark Matter around BHs

Energy losses:

$$\dot{E}_{\rm orb} = -\dot{E}_{\rm GW} - \dot{E}_{\rm DF}$$



Eda+ PRL 110, 221101 (2013)

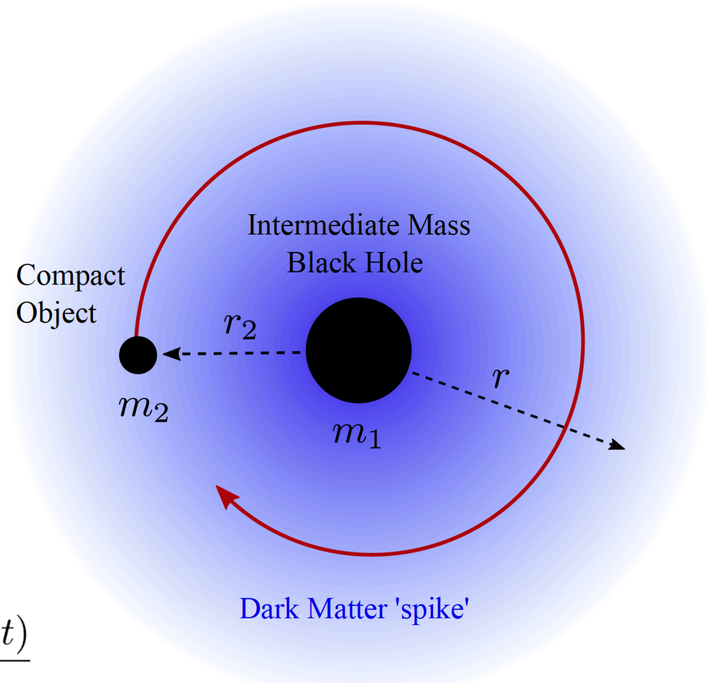
Dark Matter around BHs

Energy losses:

$$\dot{E}_{\rm orb} = -\dot{E}_{\rm GW} - \dot{E}_{\rm DF}$$

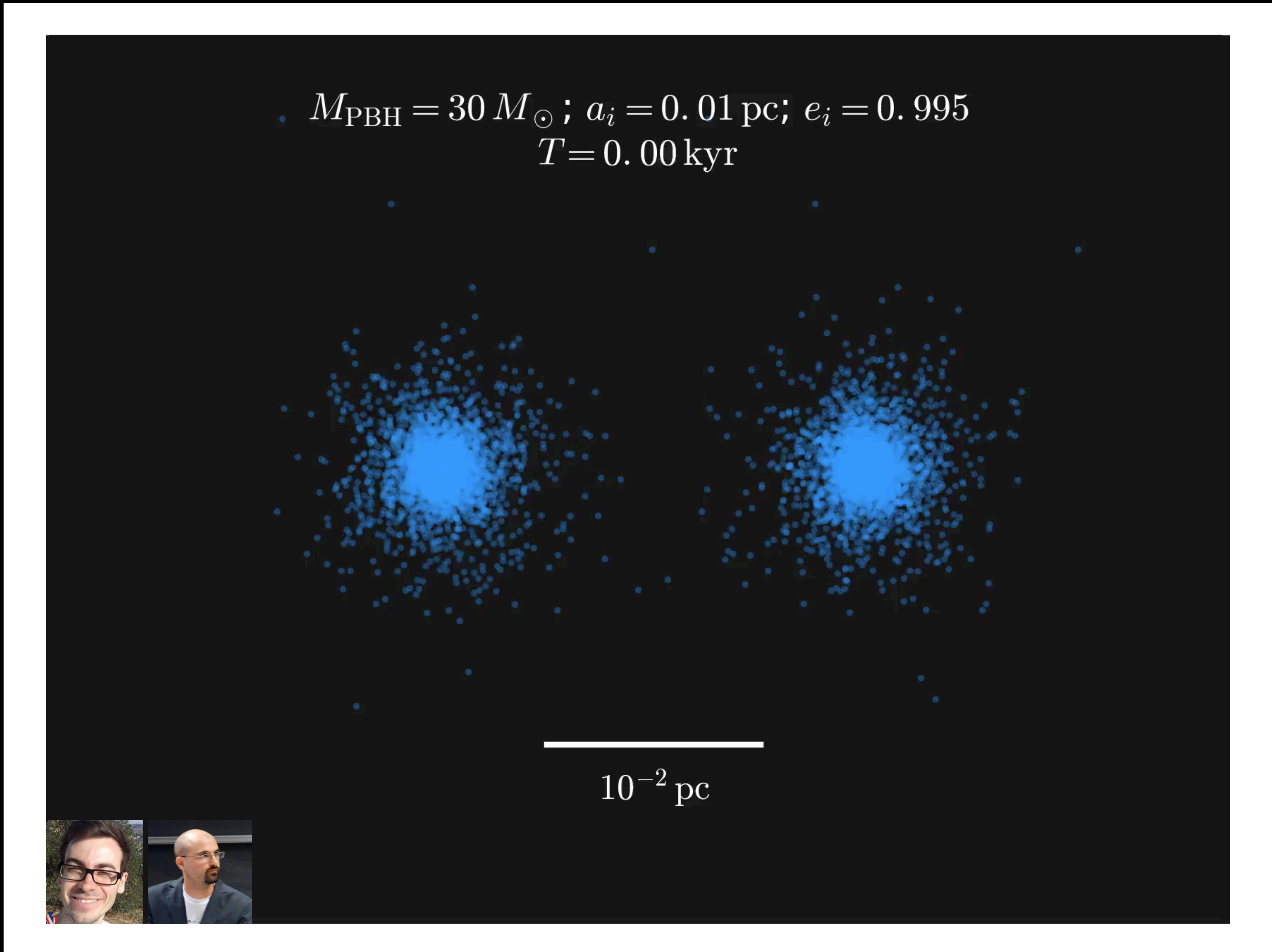
Separation:

$$\dot{r}_2 = -\frac{64\,G^3\,M\,m_1\,m_2}{5\,c^5\,(r_2)^3} - \frac{8\pi\,G^{1/2}\,m_2\,\log\Lambda r_2^{5/2}\,\rho_{\rm DM}(r_2,t)\,\xi(r_2,t)}{\sqrt{M}m_1}$$



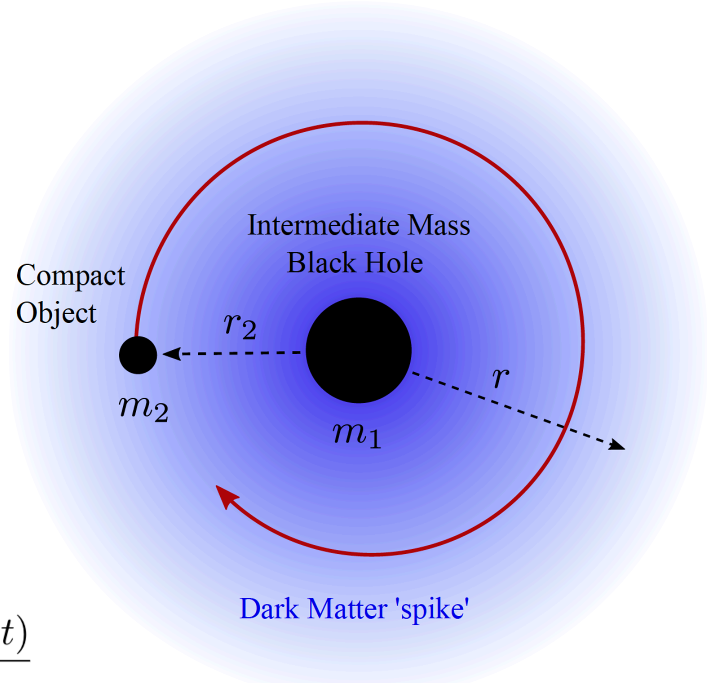
Kavanagh, GB et al. 2002.12811

'Dressed' BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

Dark Matter around BHs



Energy losses:

$$\dot{E}_{\rm orb} = -\dot{E}_{\rm GW} - \dot{E}_{\rm DF}$$

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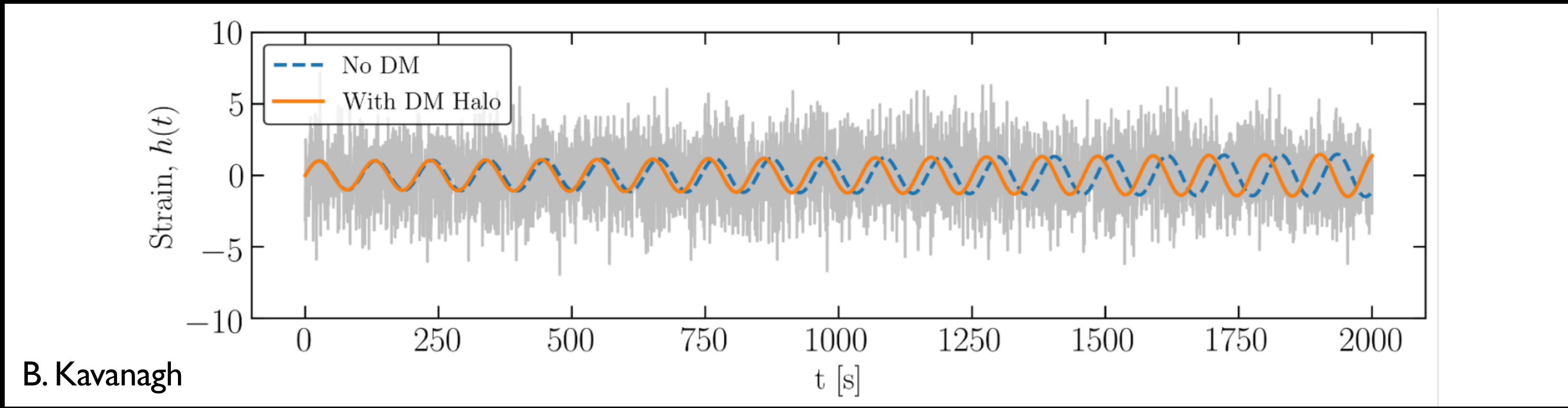
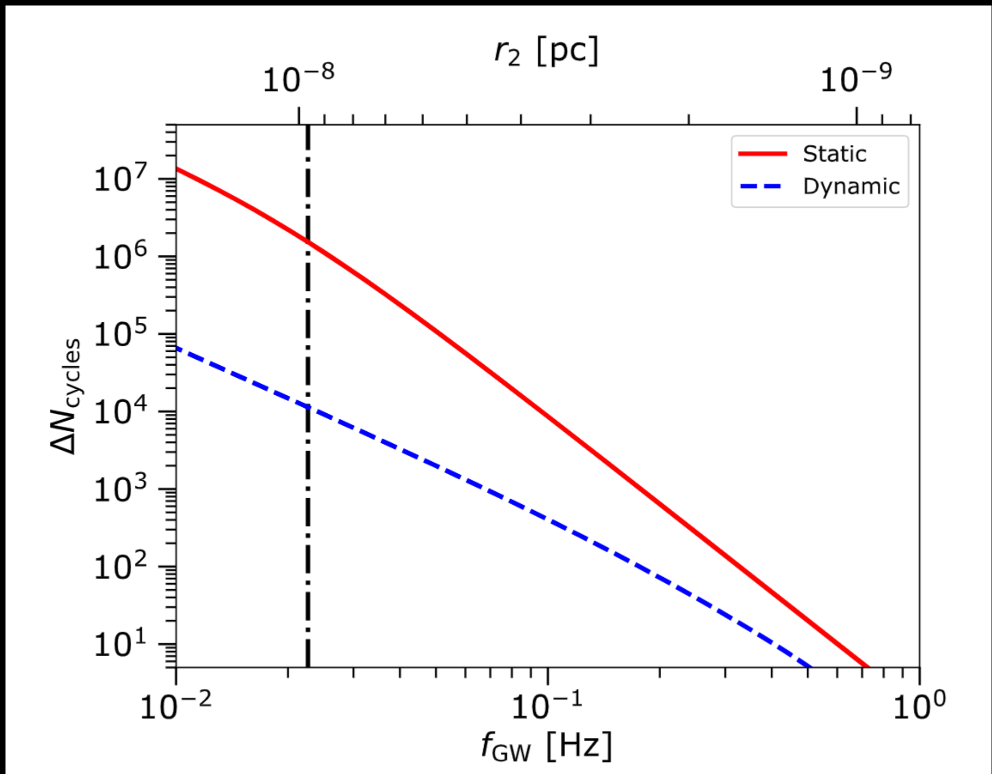
Time-dependent dark matter profile:

$$T_{\rm orb}\frac{\partial f(\mathcal{E},t)}{\partial t} = -p_{\mathcal{E}} f(\mathcal{E},t) + \int \left(\frac{\mathcal{E}}{\mathcal{E}-\Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E}-\Delta\mathcal{E},t) P_{\mathcal{E}-\Delta\mathcal{E}}(\Delta\mathcal{E})\, \mathrm{d}\Delta\mathcal{E}$$

Kavanagh, GB et al. 2002.12811

Gravitational Waveform dephasing

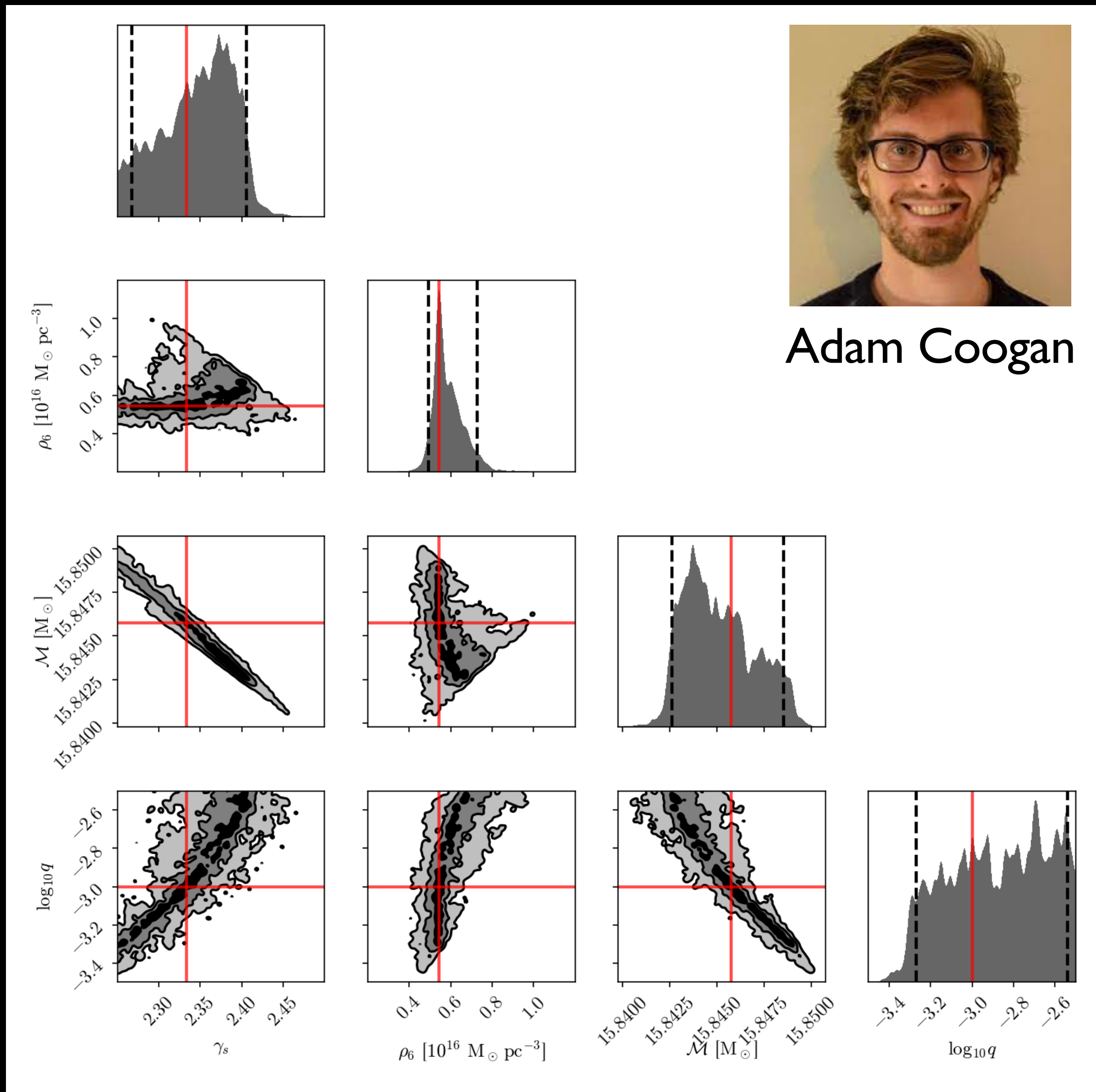




- Dark matter modifies binary dynamics via dynamical friction (Eda+ 2013, 2014)
- This induces a dephasing of the waveform, potentially detectable e.g. with LISA
- Dephasing is smaller than previously thought (i.e. wrt to case with fixed dark matter profile) but still potentially detectable

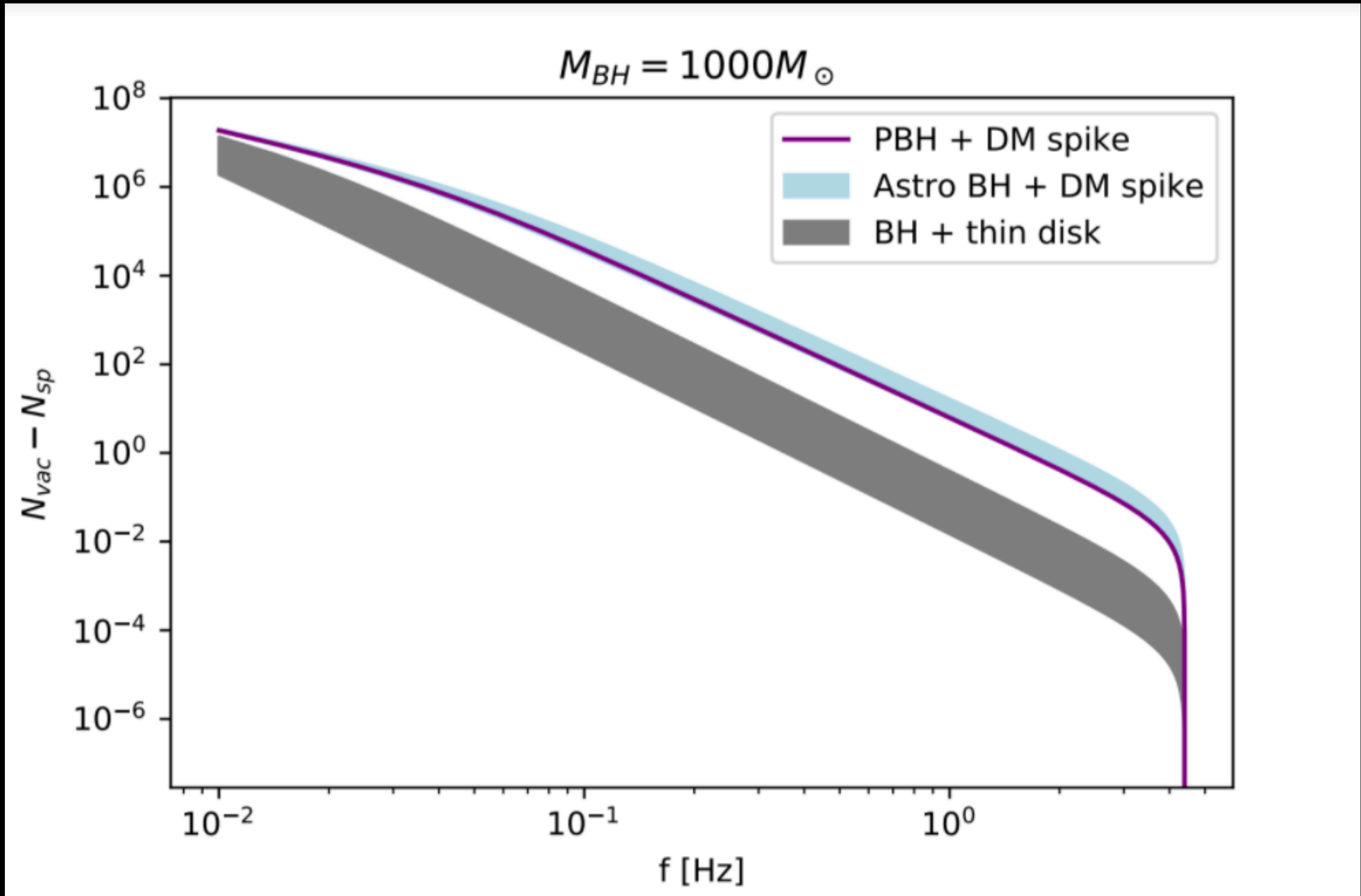
Kavanagh, GB et al. PRD 102 (2020) 8, 083006

Bayesian method to assess Detectability/ Discoverability/Measurability with LISA



Coogan, GB +, in preparation

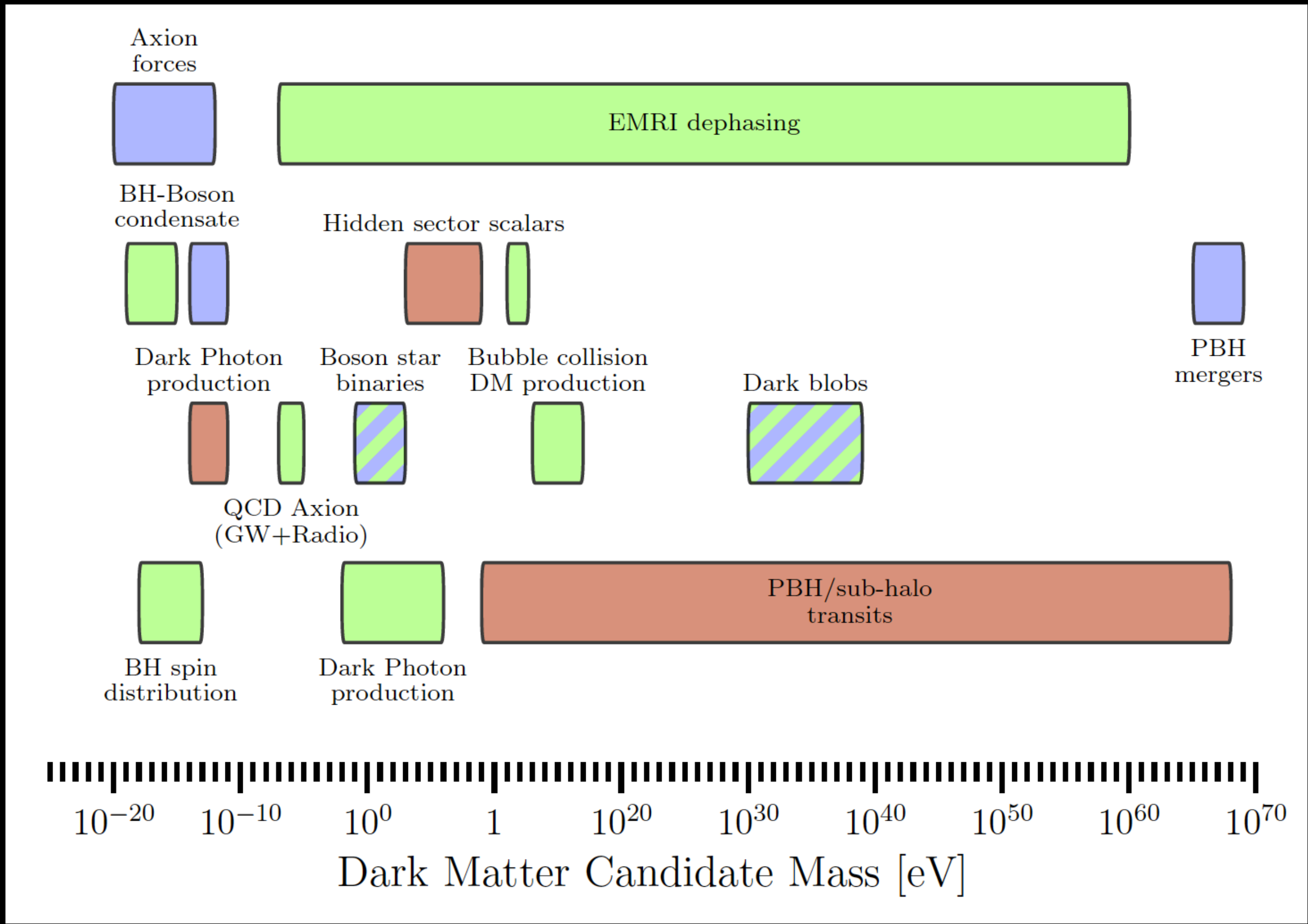
Dephasing: Model comparison / parameter estimation with LISA



Pippa Cole

Cole, GB + in preparation

Further GW-DM connections:



"Gravitational wave probes of dark matter: challenges and opportunities"
GB, Croon, et al. SciPostPhysCore 3, 007 (2020)

Conclusions

- This is a time of profound transformation for dark matter studies, in view of the absence of evidence (though NOT evidence of absence) of popular candidates

- LHC, ID and DD experiments may still reserve surprises!

- At the same time, it is urgent to:
    - Diversify dark matter searches
    - Exploit astronomical observations
    - Exploit gravitational waves

- The field is completely open: extraordinary opportunity for new generation to come up with new ideas and discoveries

First EuCAPT Annual Symposium

5-7 May 2021
CERN
Europe/Zurich timezone

Search...

*** 09/02/2021: the Symposium will be held in **fully remote mode**. Registration is now open ***

21/12/2020: invited speakers and area conveners announced.

The European Consortium for Astroparticle Theory (EuCAPT, https://www.eucapt.org) is a new initiative, with central hub at CERN, that aims to bring together the European community of theoretical astroparticle physicists and cosmologists. Our goals are to increase the exchange of ideas and knowledge; to coordinate scientific and training activities; to help scientists attract adequate resources for their projects; and to promote a stimulating, fair and open environment in which young scientists can thrive. More than 660 scientists completed the 1st EuCAPT census in January 2020, and expressed an interest in EuCAPT activities.

We are delighted to announce the first edition of the EuCAPT annual symposium, the flagship event of our consortium, that aims to provide an interdisciplinary Europe-wide forum to discuss opportunities and challenges in Theoretical Astroparticle Physics and Cosmology. We invite all scientists (PhD students, postdocs, and staff) active in these fields of research to join us remotely from May 5 to May 7, 2021. The symposium will feature invited presentations, and young scientists will have the opportunity to present their work with lightning talks. Beside scientific presentations, the programme also includes: thematic parallel discussions; a plenary session dedicated to the planning of a community-wide white paper; an award ceremony for the best talks from young scientists.

Primordial Black Holes

Mon. Not. R. astr. Soc. (1971) **152,** 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

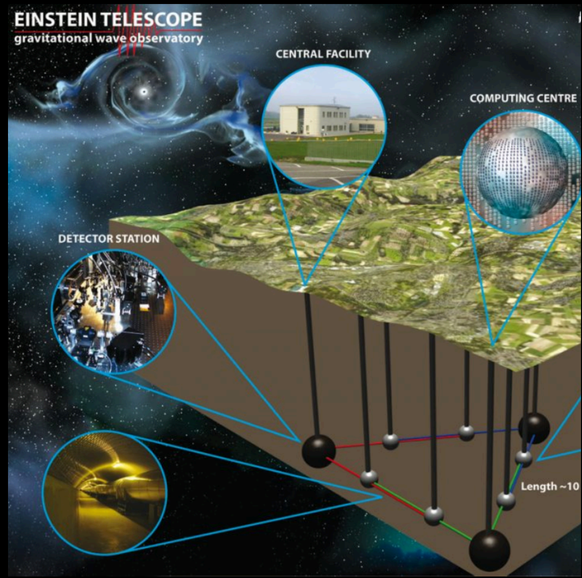
(Communicated by M. J. Rees)

(Received 1970 November 9)

An upper bound on the number of these objects can be set from the measurements by Sandage (7) of the deceleration of the expansion of the Universe. These measurements indicate that the average density of the Universe cannot be greater than about 10^{-28} g cm^{-2}. Since the average density of visible matter is only about 10^{-31} g cm^{-2}, it is tempting to suppose that the major part of the mass of the Universe is in the form of collapsed objects. This extra density could stabilize clusters of galaxies which, otherwise, appear mostly not to be gravitationally bound.

Can we convincingly discover *primordial* BHs?

Yes, e.g. if we:

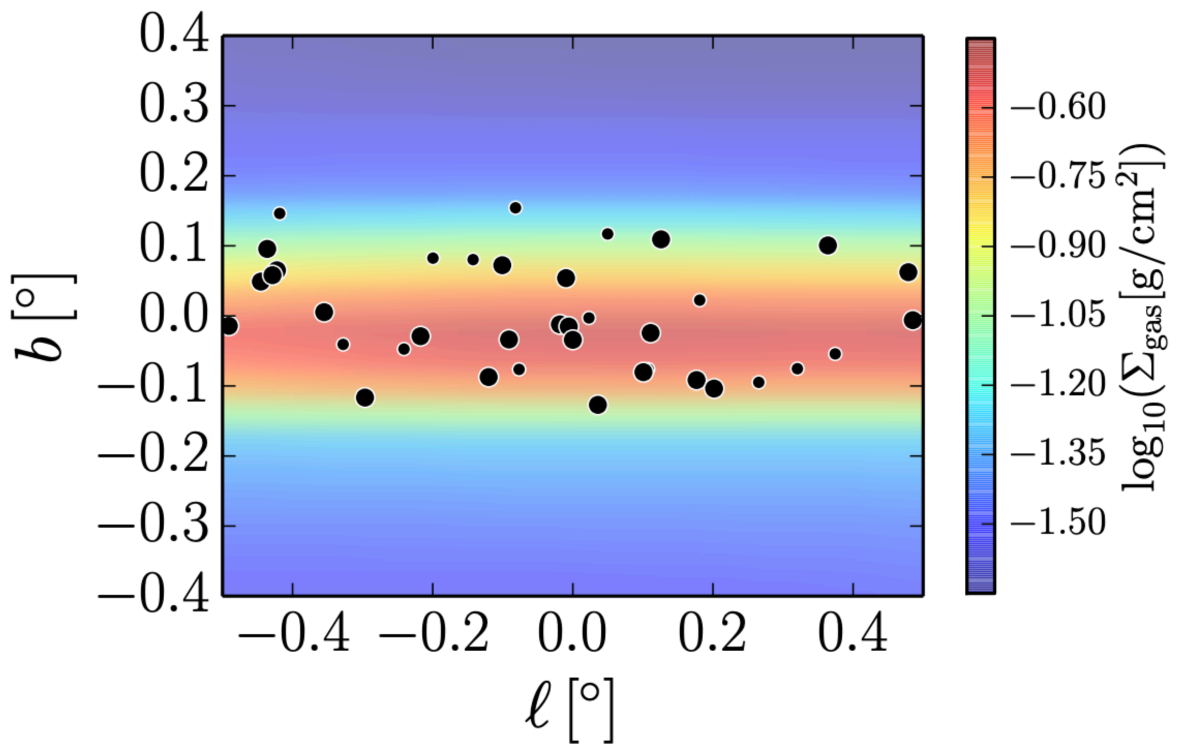


I. Detect sub-solar mass BHs with joint Ligo/Virgo observing run 3 (in progress)

II. Detect O(100) Msun BHs at very high-z (z > 40) with Einstein Telescope (e.g. 1708.07380)

III. Discover ‘unique’ radio signature with Square Kilometre Array [tricky]

Multiwavelength observations of PBHs (and astrophysical BHs) in the MW



Gaggero, GB et al. PRL 118, 241101 (2017)

- Isolated BH moving at supersonic speed in ISM produce radio and X-ray emission. Exciting prospects for detecting primordial and astrophysical BHs with SKA *[Manshanden, Gaggero+ JCAP 06 (2019) 02, Scarcella, Gaggero+, 2012.10421]*